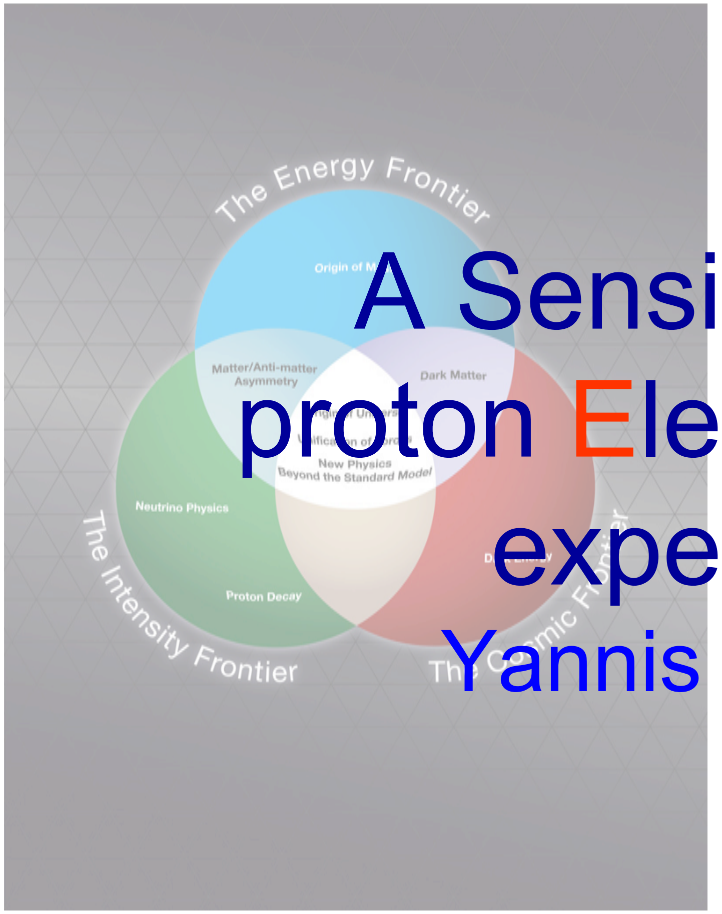
Project-X Workshop
Fermilab, 16 June 2012



A Sensitive Storage-Ring proton Electric Dipole Moment experiment at FNAL

Yannis K. Semertzidis, BNL

✓Goal: 10^{-29}e•cm; Probe New Physics >10^3 TeV and 10^4 TeV with a possible upgrade.

✓Systematics best in an all-electric ring and counter-rotating (CR) beams.

pEDM: Revolution in statistics

- Present limit from the nEDM: $3\times10^{-26}e\cdot$cm, statistics limited
- Neutron source: secondary (protons on target produce a wide energy-range neutrons). Similar production process with muons (current 10^{-19}; future $10^{-21}e\cdot$cm; dedicated $10^{-24}e\cdot$cm)

- Proton source is primary: 10^{11}protons per pulse, high polarization, narrow phase-space parameters, long lifetime…! Project-X: narrower phase-space parameters?

EDMs of hadronic systems are mainly sensitive to

- Theta-QCD (part of the SM)

- CP-violating sources beyond the SM

Alternative simple systems are needed to be able to differentiate the CP-violating source (e.g. neutron, proton, deuteron,…).

pEDM at 10^{-29}e•cm is > an order of magnitude more sens. than the current best nEDM plans

Measure all three: proton, deuteron and neutron EDMs to determine CPV source

Complementary information

$$d_n \simeq 1.4(d_d - 0.25d_u) + 0.83e(d_u^c + d_d^c) - 0.27e(d_u^c - d_d^c)$$

$$d_p \simeq 1.4(d_d - 0.25d_u) + 0.83e(d_u^c + d_d^c) + 0.27e(d_u^c - d_d^c)$$

Improved theoretical estimation on the lattice would help!

$$d_N^{I=1} \simeq 0.87(d_u - d_d) + 0.27e(d_u^c - d_d^c) \qquad d_N^{I=1} = (d_p - d_n)/2$$

$$d_N^{I=0} \simeq 0.5(d_u + d_d) + 0.83e(d_u^c + d_d^c) \qquad d_N^{I=0} = (d_p + d_n)/2$$

Physics reach of magic pEDM (Marciano)

- Currently: $\bar{\theta} \le 10^{-10}$, Sensitivity with pEDM: $\bar{\theta} < 0.3 \times 10^{-13}$

- **Sensitivity to new contact interaction: 3000 TeV**

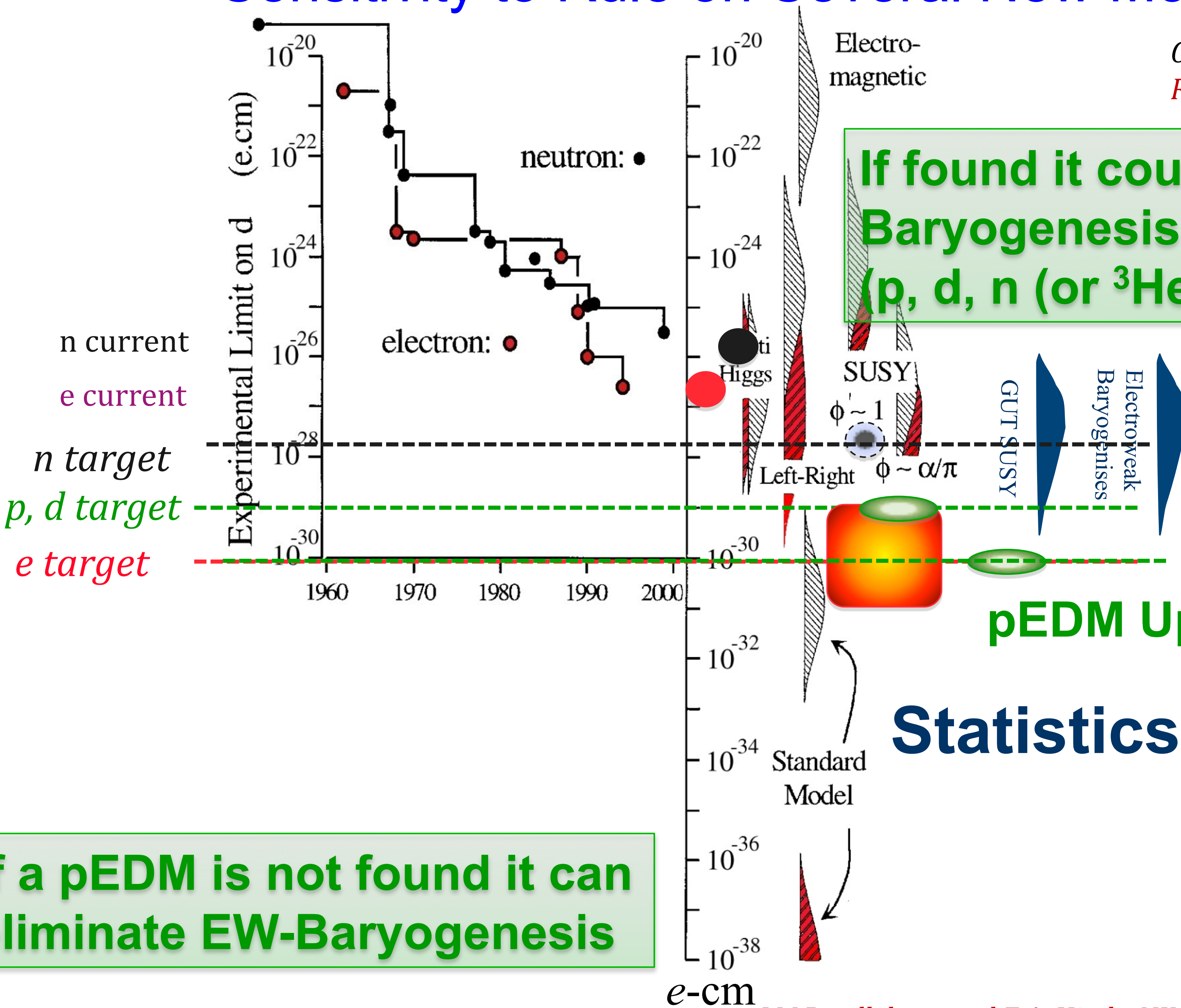
- **Sensitivity to SUSY-type new Physics:**

$$pEDM \approx 10^{-24}\,\mathrm{e \cdot cm}\ \times \sin\delta \times \left(\frac{1\mathrm{TeV}}{M_{\mathrm{SUSY}}}\right)^2$$

The proton EDM at 10^{-29}e·cm has a reach of >300TeV; it can probe fine-tuned SUSY

The deuteron EDM sensitivity is similar.

Sensitivity to Rule on Several New Models



Gray: Neutron
Red: Electron

If found it could explain Baryogenesis (p, d, n (or ^{3}He))

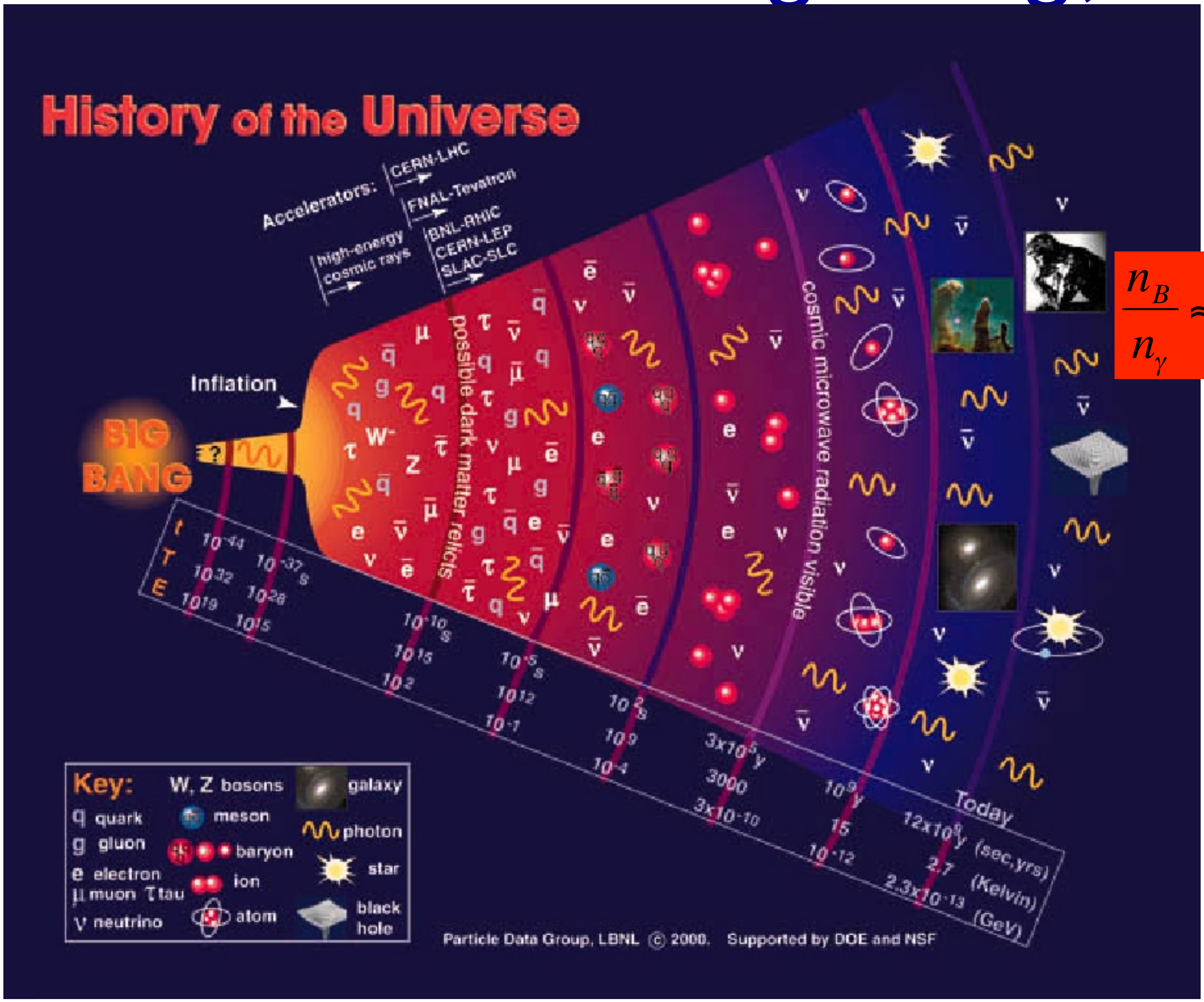
pEDM Upgrade?

Statistics limited

If a pEDM is not found it can eliminate EW-Baryogenesis

J.M.Pendlebury and E.A. Hinds, NIMA 440 (2000) 471

Why is there so much matter after the Big Bang;



We see:

$$\frac{n_B}{n_\gamma} \approx (6.08 \pm 0.14) \times 10^{-10}$$

From the SM:

$$\frac{n_B}{n_\gamma} = \frac{n_{\bar{B}}}{n_\gamma} \approx 10^{-18}$$

Short History of EDM

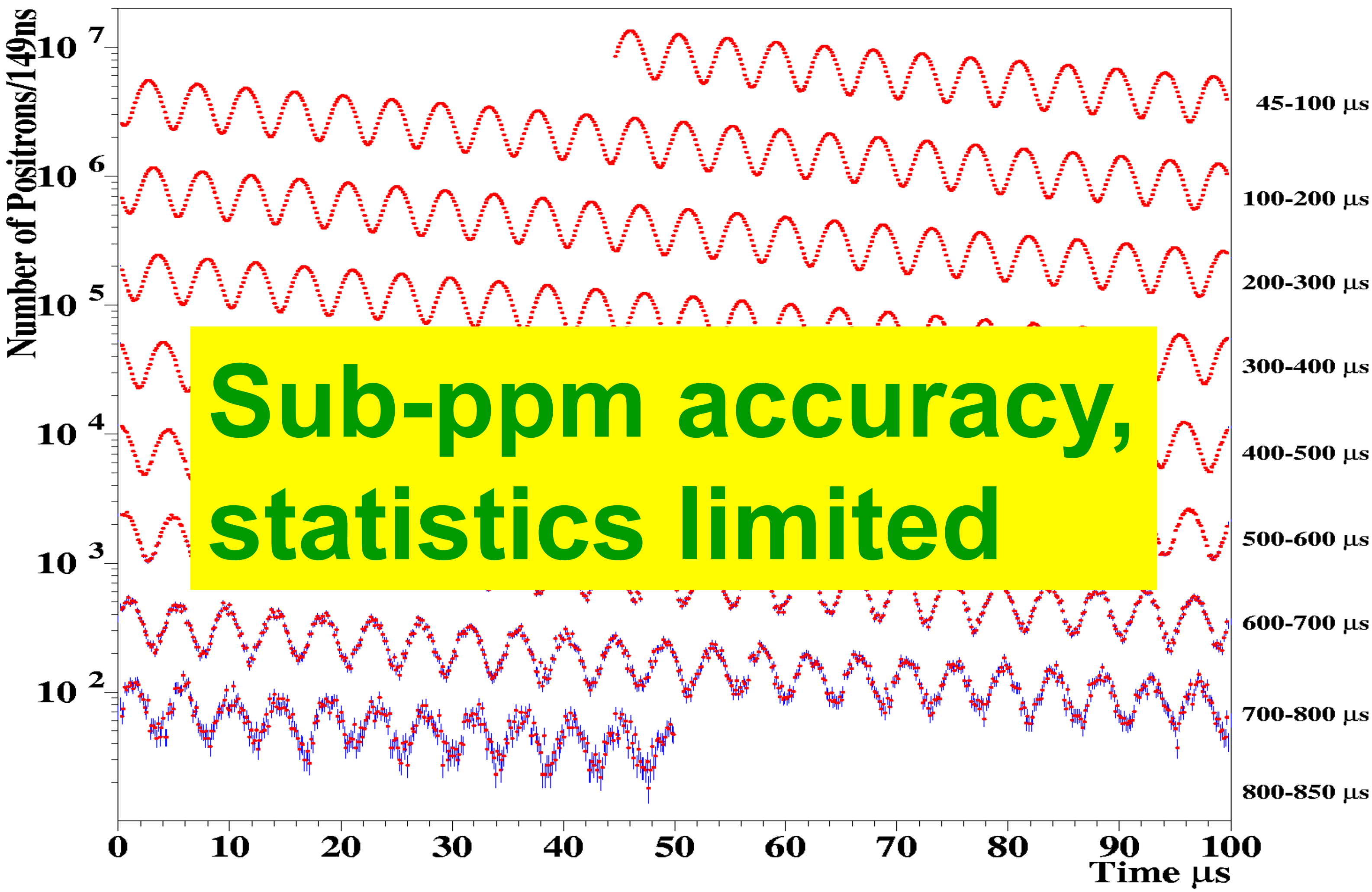
- 1950's neutron EDM experiment started to search for parity violation (Ramsey and Purcell).
- After P-violation → EDMs require both P,T-Violation
- 1960's EDM searches in atomic systems
- 1970's Indirect Storage Ring EDM method from the CERN muon g-2 exp.
- 1980's Theory studies on systems (molecules) w/ large enhancement factors
- 1990's First exp. attempts w/ molecules. Dedicated Storage Ring EDM method developed
- 2000's Proposal for sensitive dEDM exp. developed.
- 2010's Proposal for sensitive pEDM exp. developed.

- Muon g-2: Precision physics in a Storage Ring

- Statistics limited… to improve sensitivity by a factor of 4 at Fermilab

Muon g-2: 4 Billion e+ with E>2GeV

$$dN/dt = N_0 e^{-\frac{t}{\tau}}\left[1 + A\cos\left(\omega_a t + \phi_a\right)\right]$$



Breakthrough concept: Freezing the horizontal spin precession due to E-field

$$\vec{\omega}_a = \frac{e}{m}\left\{ a\vec{B} + \cancel{\left[a - \left(\frac{m}{p}\right)^2 \right] \frac{\vec{\beta}\times\vec{E}}{c}} \right\}$$

Muon g-2 focusing is electric: The spin precession due to E-field is zero at "magic" momentum (3.1GeV/c for muons, 0.7 GeV/c for protons,…)

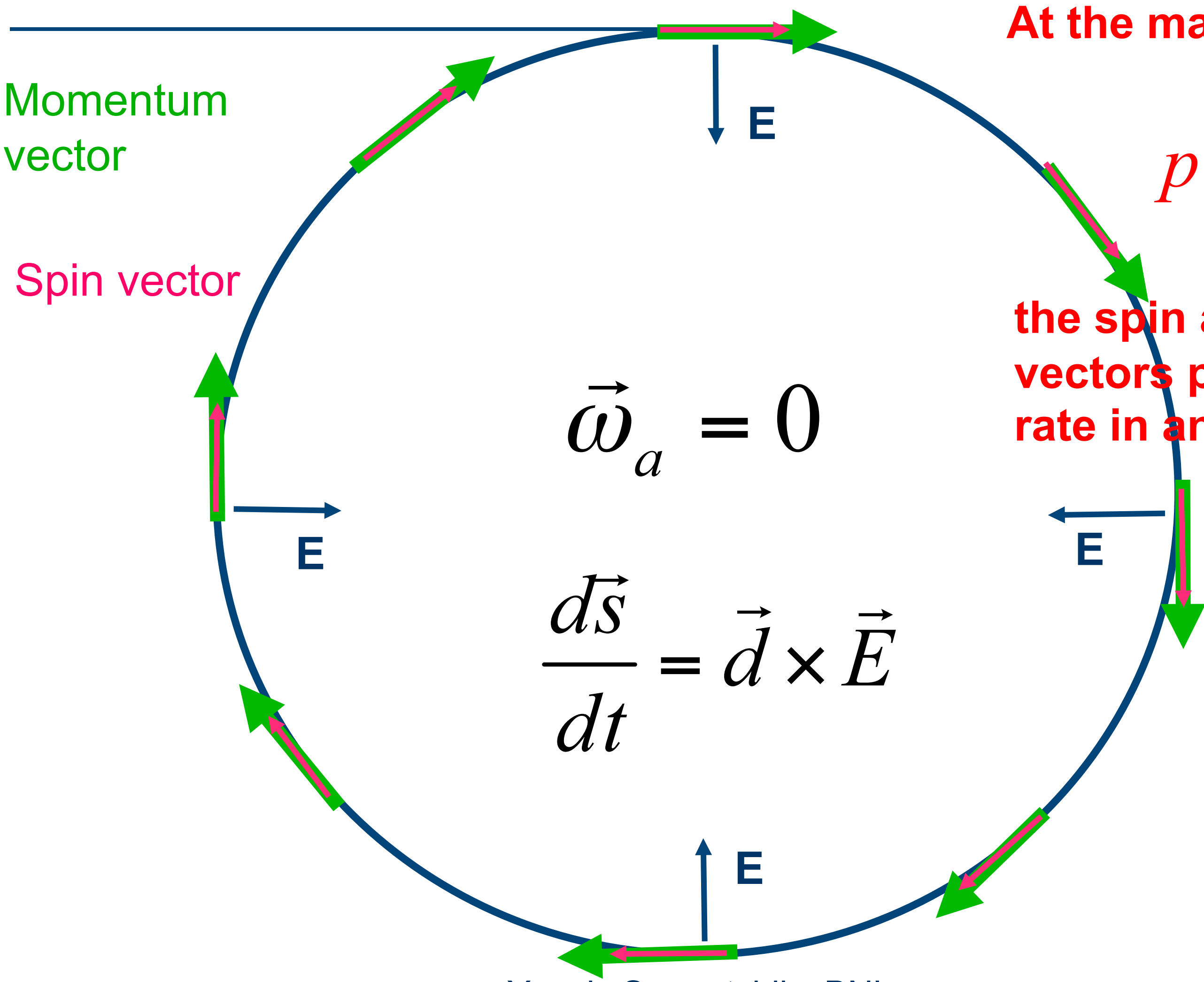
$$p = \frac{m}{\sqrt{a}}, \text{ with } a = \frac{g-2}{2}$$

The "magic" momentum concept was used in the muon g-2 experiments at CERN, BNL, and …next at FNAL.

The proton EDM uses an ALL-ELECTRIC ring: spin is aligned with the momentum vector

Momentum vector

Spin vector



$$\vec{\omega}_a = 0$$

$$\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}$$

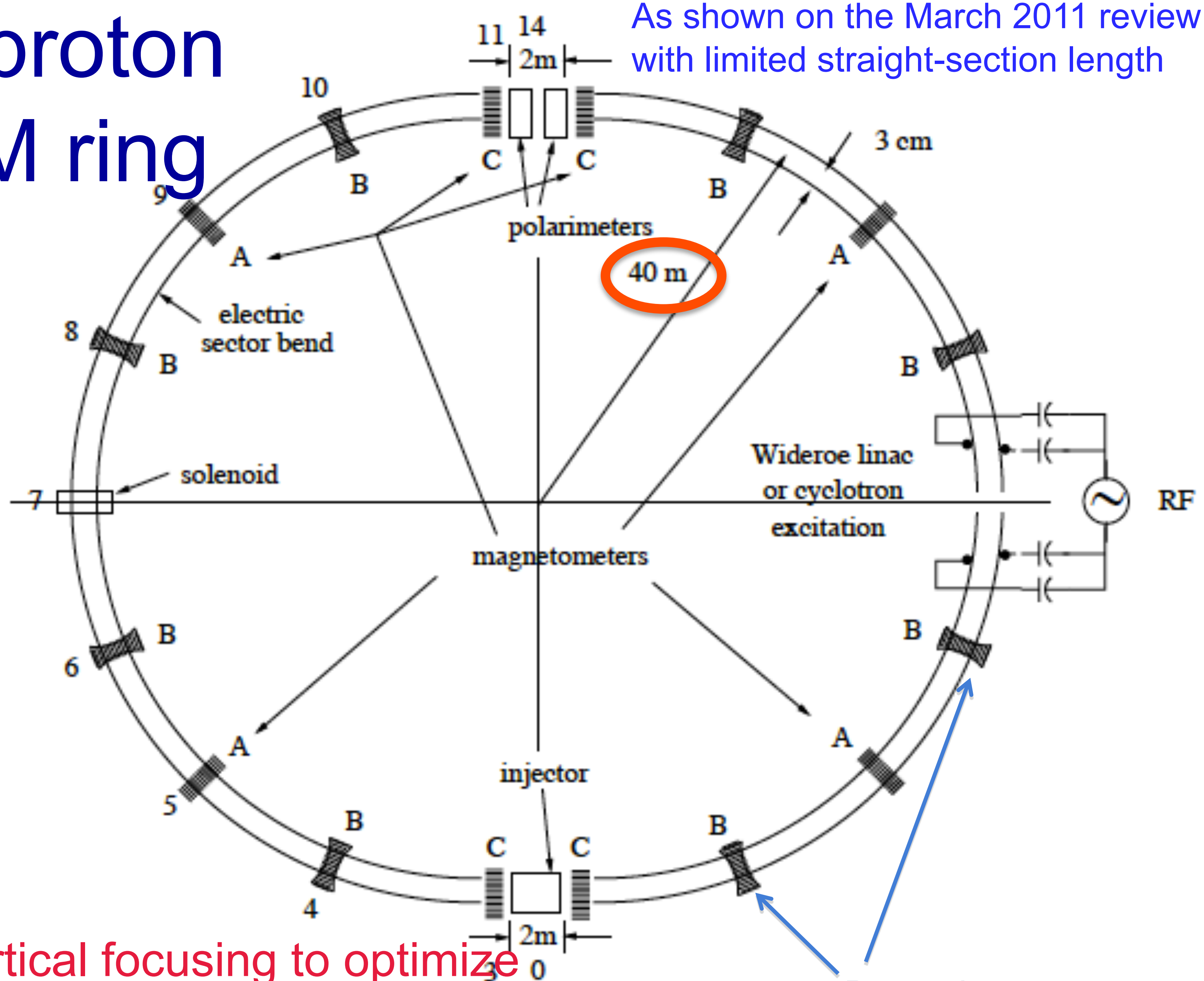
At the magic momentum

$$p = \frac{m}{\sqrt{a}}$$

the spin and momentum vectors precess at same rate in an E-field

The proton EDM ring

As shown on the March 2011 review with limited straight-section length



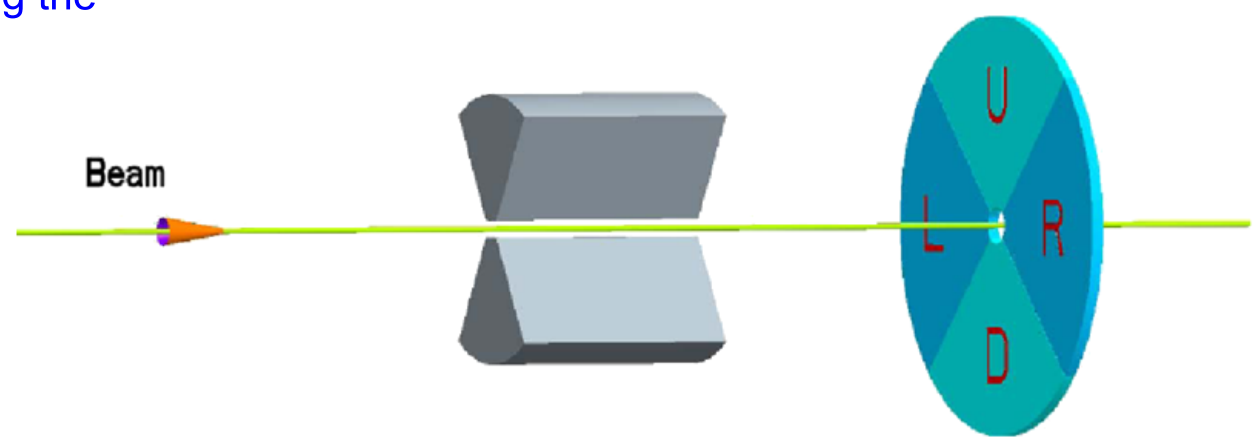
Weak vertical focusing to optimize SCT and BPM operation

pEDM polarimeter principle: probing the proton spin components as a function of storage time

"defining aperture" polarimeter target

Micro-Megas TPC detector and/or MRPC

Extraction: lowering the vertical focusing



$$\varepsilon_H = \frac{L-R}{L+R}$$

carries EDM signal
increases slowly with time

$$\varepsilon_V = \frac{D-U}{D+U}$$

carries in-plane (g-2) precession signal

Is the polarimeter analyzing power good at P_{magic}? YES!

Analyzing power can be further optimized

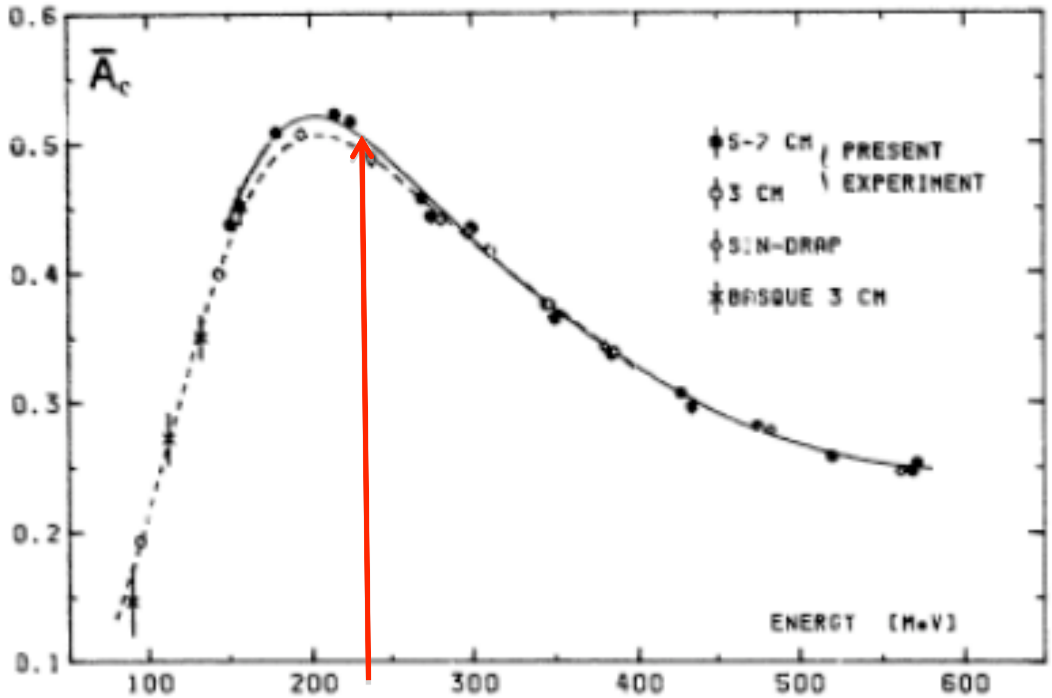


Fig. 4. Angle-averaged effective analyzing power. Curves show our fits. Points are the data included in the fits. Errors are statistical only

Fig.4. The angle averaged effective analyzing power as a function of the proton kinetic energy. The magic momentum of 0.7GeV/c corresponds to 232MeV.

Proton Statistical Error (230MeV):

$$\sigma_d = \frac{2\hbar}{E_R P A \sqrt{N_c f \tau_p T_{tot}}}$$

τ_p : 10^3s Polarization Lifetime (Spin Coherence Time)
A : 0.6 Left/right asymmetry observed by the polarimeter
P : 0.8 Beam polarization
N_c : 4×10^{10}p/cycle Total number of stored particles per cycle
T_{Tot}: 10^7s Total running time per year
f : 0.5% Useful event rate fraction (efficiency for EDM)
E_R : 10.5 MV/m Radial electric field strength (95% azim. cov.)

$$\sigma_d = 1.6\times10^{-29}\,\mathrm{e\cdot cm/year}\ \text{for uniform counting rate and}$$

$$\sigma_d = 1.1\times10^{-29}\,\mathrm{e\cdot cm/year}\ \text{for variable counting rate}$$

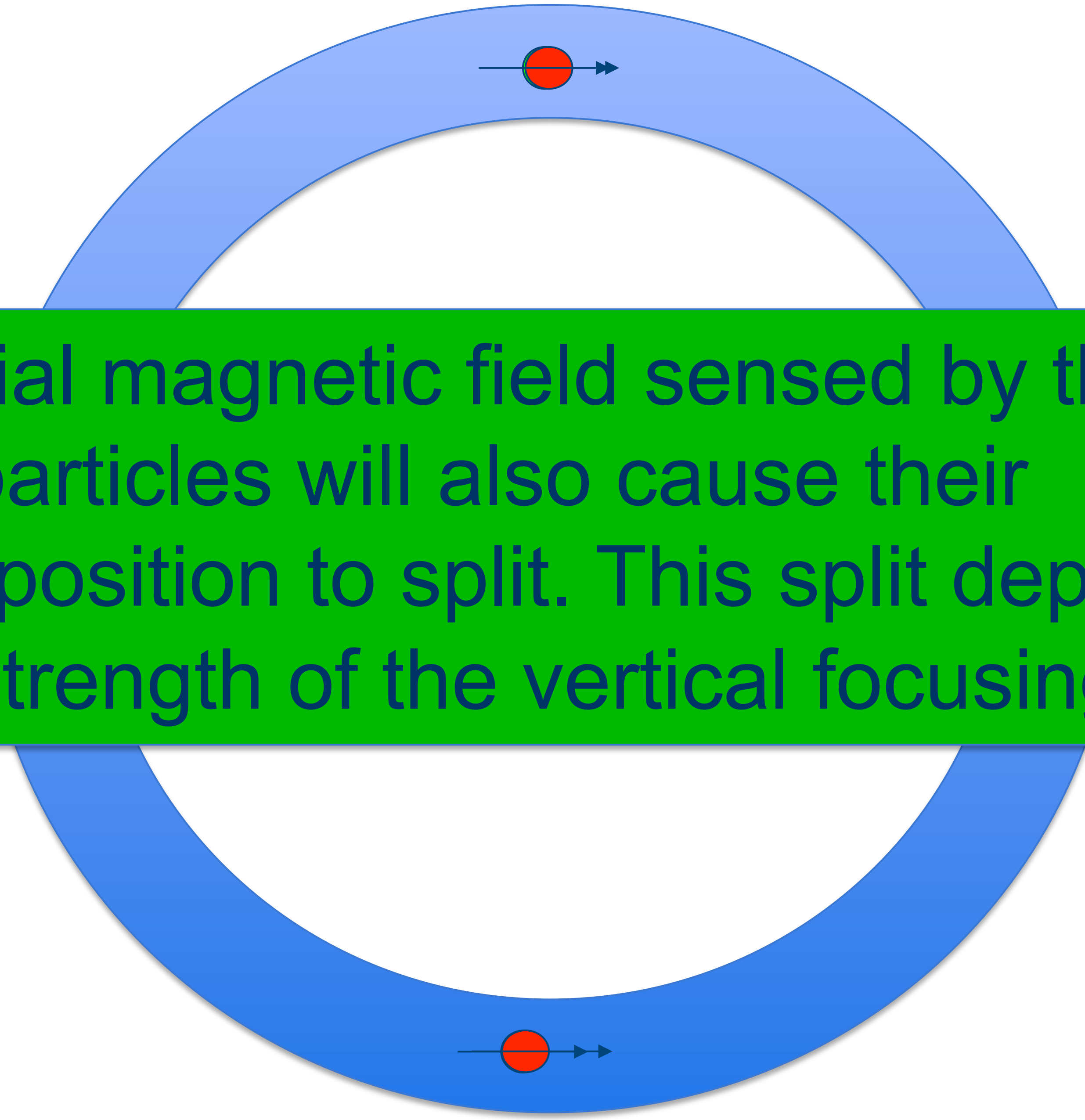
Systematic errors

- ✓ Polarimeter (detector) related. We have shown with stored polarized deuteron beams at COSY/ Germany to be << our sensitivity; Stephenson et al.

- ✓ Geometrical phases are << our sensitivity for measured ground (position) stability at Fermilab.

- Radial magnetic field integrated around the ring (use the beam to probe it!); D. Kawall et al.

Clock-wise (CW) & Counter-Clock-wise Storage



Any radial magnetic field sensed by the stored particles will also cause their vertical position to split. This split depends on the strength of the vertical focusing…

Beam Position Monitors magnetometers

- Technology of choice: Low T_c SQUIDS, signal at 10^2-10^4Hz (10% vertical tune modulation)
- R&D sequence: (First funding from US-Japan)

1. Operate SQUIDS in a magnetically shielded area-reproduce current state of art
2. Operate in RHIC at an IP (evaluate noise in an accelerator environment);
3. Operate in E-field string test

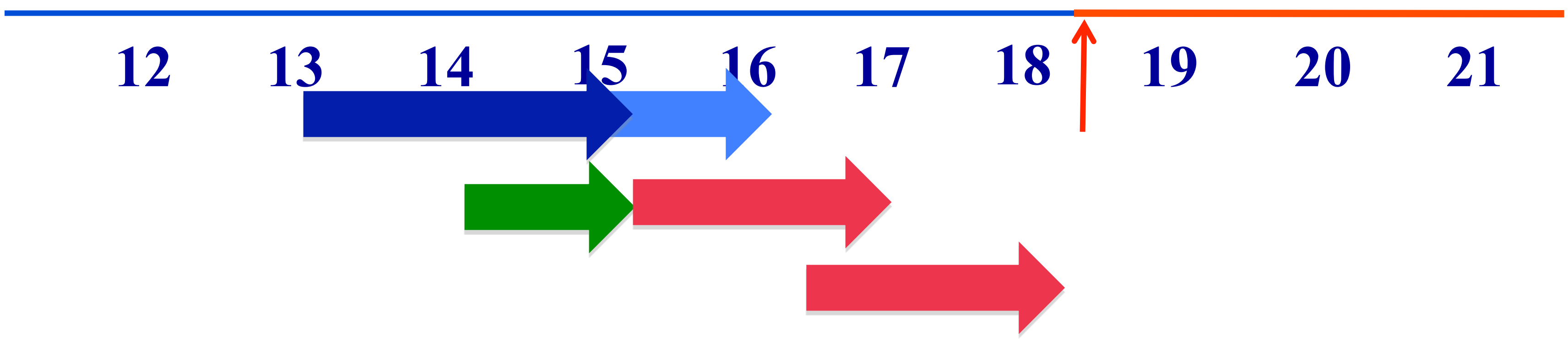
The miracles that make the pEDM

1. Magic momentum (MM): high intensity (10^{11}), high polarization (>80%), proton beams in an all-electric storage ring
2. High analyzing power: A>50% at the MM
3. Weak vertical focusing in an all-electric ring: SCT allows for 10^3s beneficial storage and 10^{-29}e•cm/year is feasible. Prospects for longer SCT with mixing (cooling and heating) under study (aim for 10^{-30}e•cm).
4. The beam vertical position tells the average radial B-field; the main systematic error source

The R&D program is very successful

- ✓ Polarimeter development: high efficiency, small systematic errors.
- ✓ Spin Coherence Time (SCT): study at COSY/ simulations; Simulations for an all-electric ring: SCT and systematic error studies.
- ✓ Electric field development for small surface area plates extrapolated to large area plates.
- BPM magnetometers (need to demonstrate in a storage ring environment). Secured first funding from the US/Japan program.

Technically driven pEDM timeline



- Two years R&D/preparation
- One year final ring design
- Two years ring/beam-line construction
- Two years installation
- One year “string test”

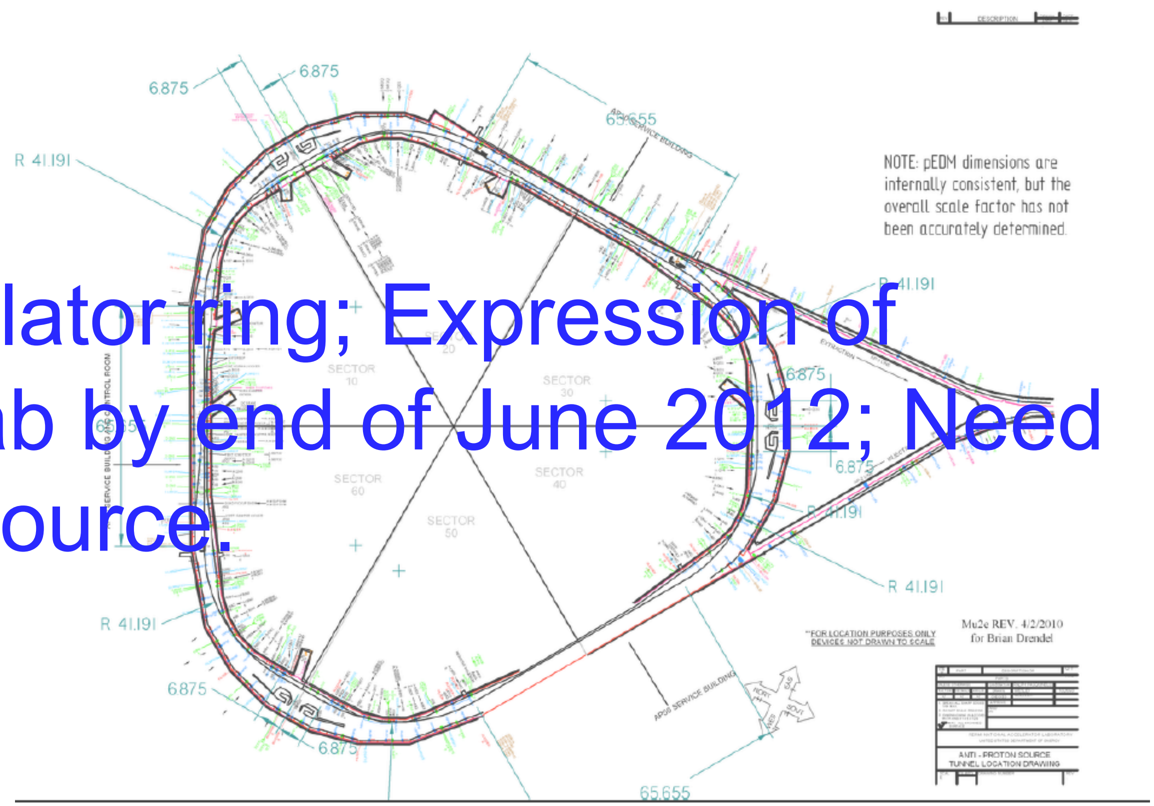
Scientific and technical reviews

- BNL PAC, March 2008: Enthusiastic on the Physics reach…
- We had two successful technical reviews: Dec 2009, and March 2011.
- Sent a proposal to DOE NP for a proton EDM experiment at BNL: November 2011

Other possible places?

- COSY (Jülich/Germany); proposal for a pre-cursor experiment; we have a common R&D collaboration.

- Fermilab, accumulator ring; Expression of Interest to Fermilab by end of June 2012; Need polarized proton source.



Common R&D with COSY

EDM at Storage Rings

JÜLICH
FORSCHUNGSZENTRUM

International srEDM Network

Institutional (MoU) and Personal (Spokespersons …) Cooperation

srEDM Collaboration (BNL)	srEDM Collaboration (FZJ)

Common R & D

RHIC	EDM-at-COSY
Beam Position Monitors	Polarimetry
(…)	Spin Coherence Time
	Cooling
	(…)

Spin Tracking

Slide by H. Stroeher, Director of IKP II

	Study Group
DOE-Proposal	Precursor; Ring Design
CD0, 1, …	HGF Application(s)

Proton EDM ring lattice using the accumulator tunnel at FNAL

Lattice by R. Talman;
230 MeV protons

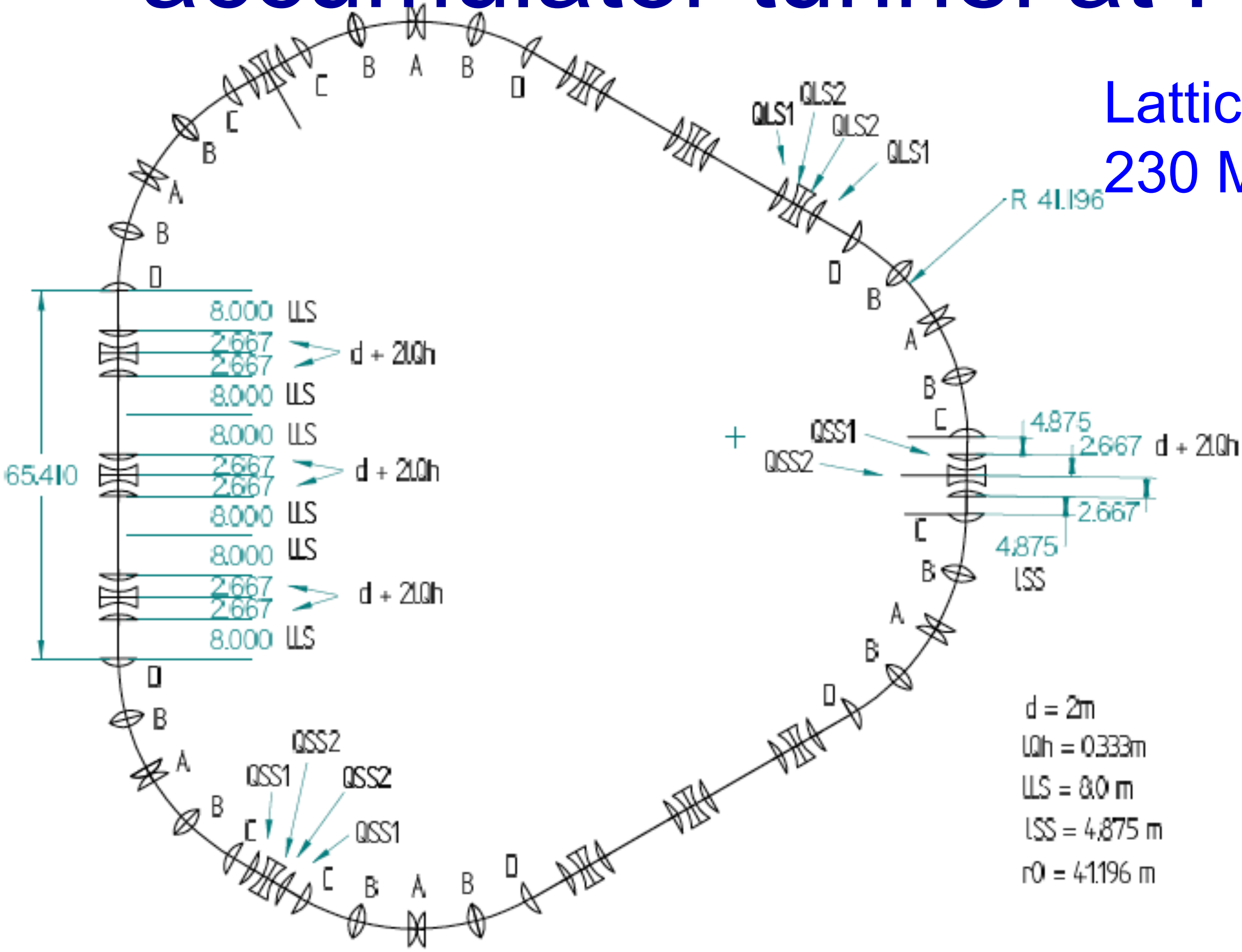


Figure 12: Dimensions and nomenclature for the pEDM in FNAL accumulator ring tunnel.

How can we make a proton EDM experiment at FNAL reality?

In red: Polarized proton source (new)

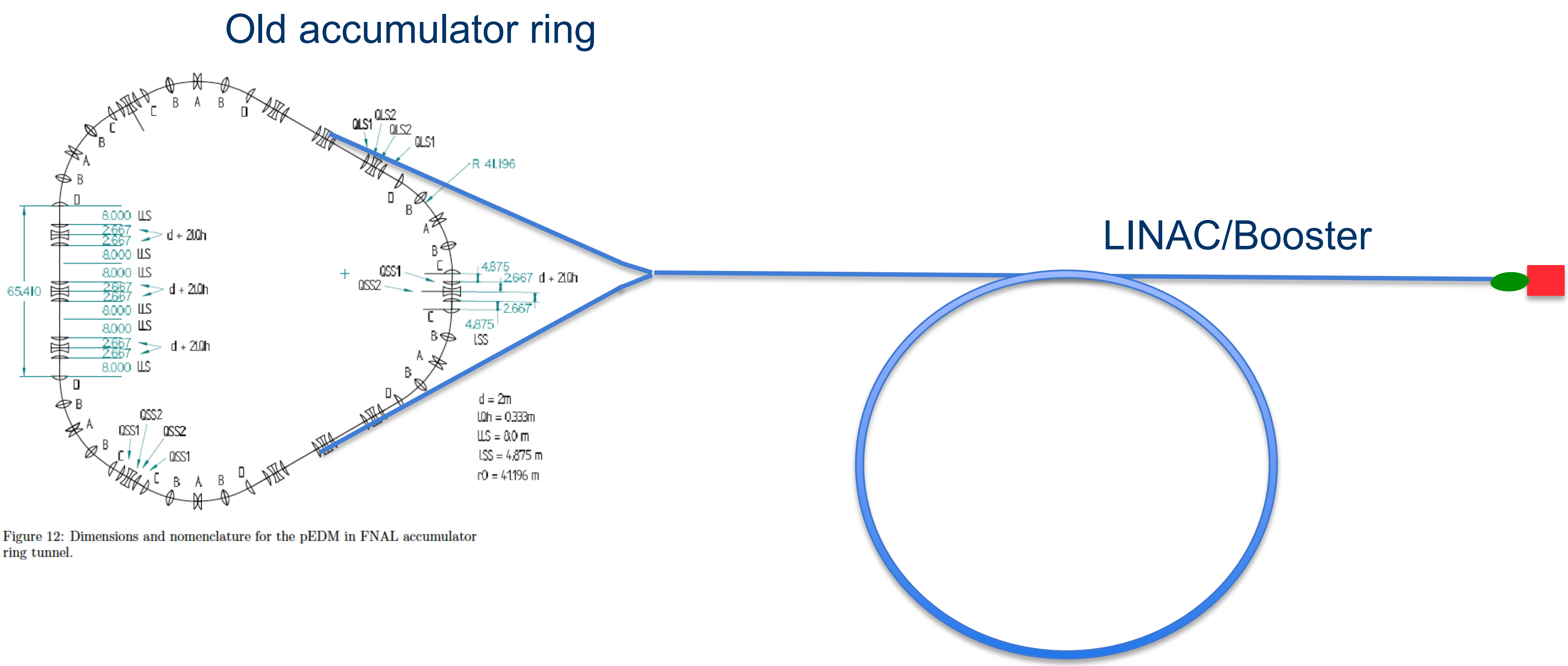
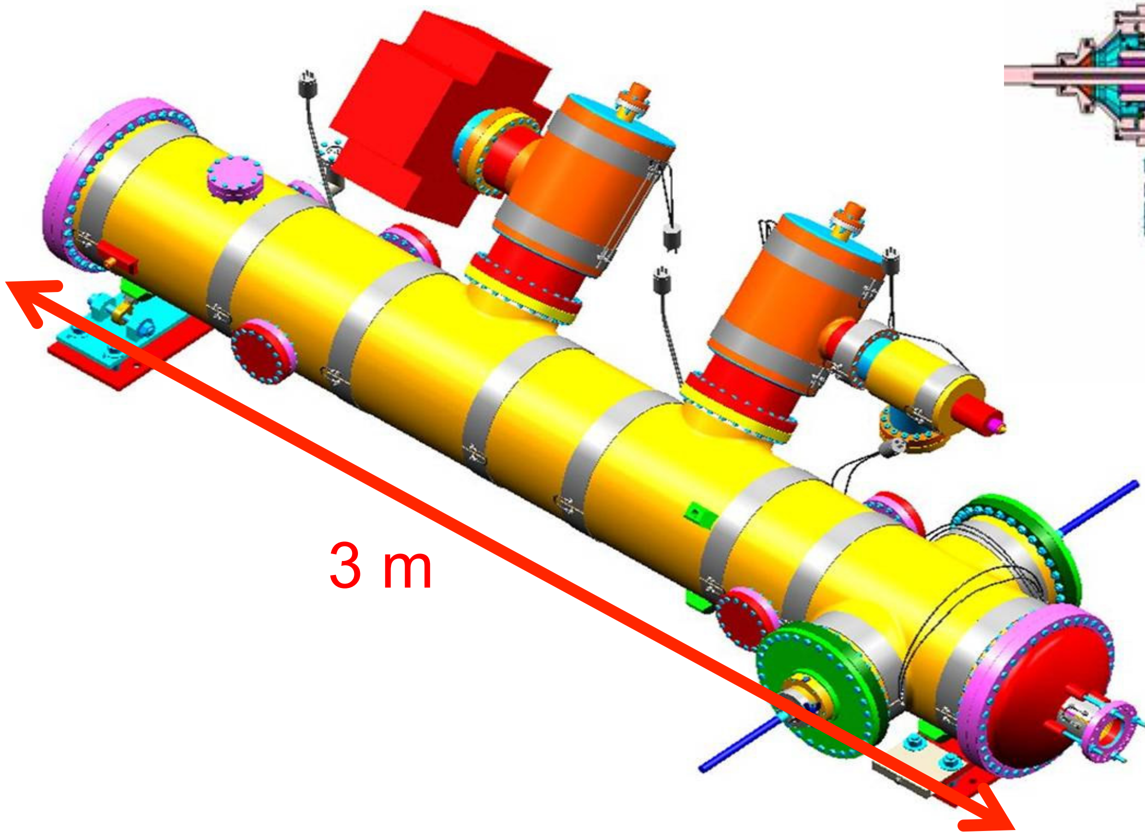
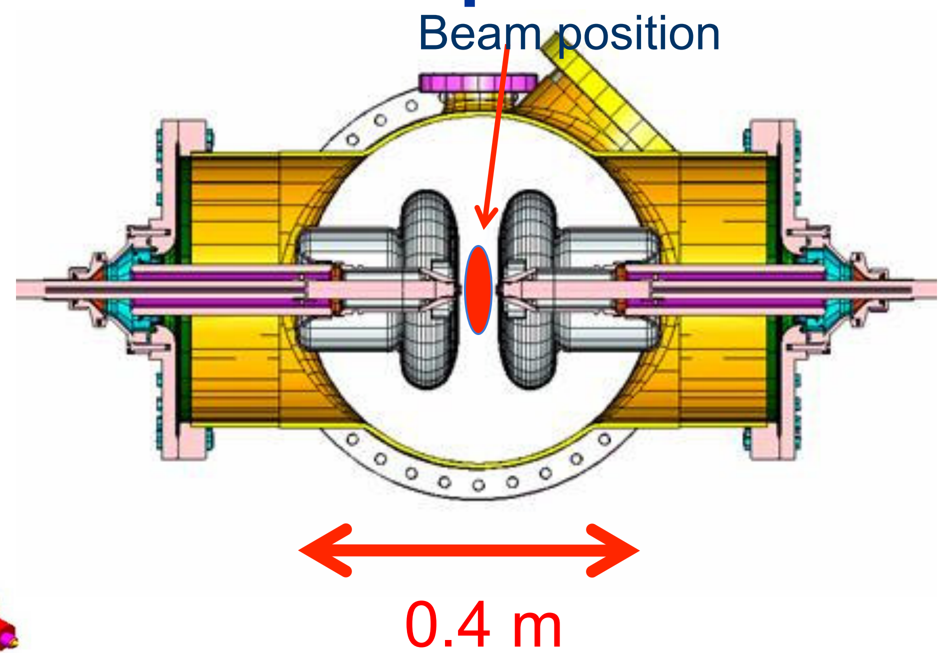


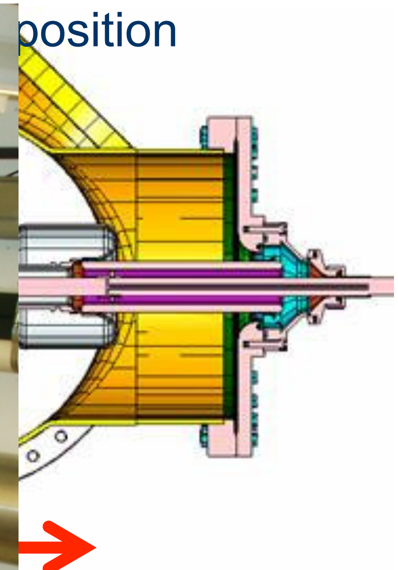
Figure 12: Dimensions and nomenclature for the pEDM in FNAL accumulator ring tunnel.

E-field plate module: Similar to the (26) FNAL Tevatron ES-separators





E-field plate module: Similar to the (26) FNAL Tevatron ES-separators



How can we make a proton EDM experiment at FNAL reality?

- Proton EDM proposal to FNAL (need support for the proposal; srEDM a HEP project)
- Polarized proton source and polarized beam experts at FNAL
- Store counter-rotating proton beams (230 MeV)
- Possible pEDM upgrades:

1. Study stochastic cooling possibility
2. Project-X: high intensity polarized proton beams, scrape beams for very long SCT

Physics/effort comparison

- Physics reach ~10^3-10^4 TeV, moreover, it can explain BAU (EW-Baryogenesis)
- SUSY-like new physics at LHC scale, it probes CP-violating phases to sub micro-radian level, complementary to LHC (plus fine-tuned SUSY)
- At 10^{-29}e·cm it's > an order of magnitude better than the best hadronic EDM plans anywhere. Statistically superior to hadronic EDM exps.
- Method can be applied to proton, deuteron, and ^{3}He (neutron equiv.) to unravel the underlying physics. More than other EDM methods can do.

Summary

- ✓ Proton EDM physics is a must do
- ✓ E-field issues well understood
- ✓ Working EDM lattice with long SCT and large enough acceptance ($\sim 10^{-29}$ *e*•cm/year); With Stochastic cooling → ($\sim 10^{-30}$ *e*•cm).
- ✓ Polarimeter work
- Planning BPM-prototype demonstration including tests at RHIC
- Old accumulator ring could house the proton EDM ring at Fermilab; we can start now.
- ✓ Project-X may further improve sensitivity

Extra slides

Physics strength comparison (Marciano)

System	Current limit [e·cm]	Future goal	Neutron equivalent
Neutron	$<1.6\times10^{-26}$	$\sim10^{-28}$	10^{-28}
^{199}Hg atom	$<3\times10^{-29}$	$<10^{-29}$	10^{-25}-10^{-26}
^{129}Xe atom	$<6\times10^{-27}$	$\sim10^{-29}$-10^{-31}	10^{-25}-10^{-27}
Deuteron nucleus		$\sim10^{-29}$	3×10^{-29}-5×10^{-31}
Proton nucleus	$<7\times10^{-25}$	$\sim10^{-29}$	10^{-29}

arXiv:1202.1697v1 [physics.acc-ph] 8 Feb 2012

M. Conte

$$\gamma_{\rm m} = \sqrt{1+\frac{1}{a}} = 1.248 \qquad (2$$

where $a = 1.793$ is the proton anomaly. Consequently we have:

$$\begin{aligned} \beta_{\rm m} &= 0.598 \\ p_{\rm m} &= \frac{mc}{\sqrt{a}} = 0.701\ {\rm GeV/c} \\ U_{\rm m} &= \gamma_{\rm m}\, mc^2 = 1.171\ {\rm GeV} \\ W_{\rm m} &= U_{\rm m} - mc^2 = 0.233\ {\rm GeV} \\ m &= \text{proton mass} = 0.938\ {\rm GeV/c^2} \end{aligned}$$

and

$$B_{\rm eq} = \frac{E_{\rm rad}}{\beta c}, \quad \text{for} \quad E_{\rm rad} = 1.5\times 10^{7}\ {\rm Vm^{-1}} = 150\ {\rm kV/cm} \qquad (2.$$

or

$$B_{\rm eq} = 8.37\times 10^{-2}\ \text{Tesla, which yields a bending radius } \rho = \frac{p}{eB_{\rm eq}} = 28\ {\rm m} \qquad (2.$$

$$\boxed{\nu_{\rm H}^2 = 2 - \beta_0^2 = 1 + \frac{1}{\gamma_0^2}}$$

Why does the world need a Storage Ring EDM experiment at the 10^{-29} e-cm level ?

1. The proton, deuteron and neutron combined can pin-down the CP-violating source should a non-zero EDM value is discovered. Critical: they can differentiate between a theta-QCD source and beyond the SM.
2. The proton and deuteron provide a path to the next order of sensitivity.

Why Storage Ring EDMs?

- Storage rings offer a unique setting for a sensitive electric dipole moment (EDM) probe of charged particles. A number of simple systems can be probed with high accuracy: p, d, ^{3}He,…
- The mechanical (centrifugal) force balances the strong radial E-fields.
- Pencil-like, high intensity/high polarization beams of protons and deuterons have been around for decades.
- Ready for prime time.

Beam parameters

C.R. proton beams	0.7 GeV/c	≥80% polariz.;	~4×10^{10} protons/store
~10^2 m base length	Repetition period: 20 minutes	Beam energy: ~1J	Average beam power: ~1mW
Beam emittance: 95%, norm.	Horizontal: 2 mm-mrad	Vertical: 6 mm-mrad	$(dp/p)_{rms}$~ 2×10^{-4}

- CW & CCW injections: Average emittance parameters: same to ~10% at injection.

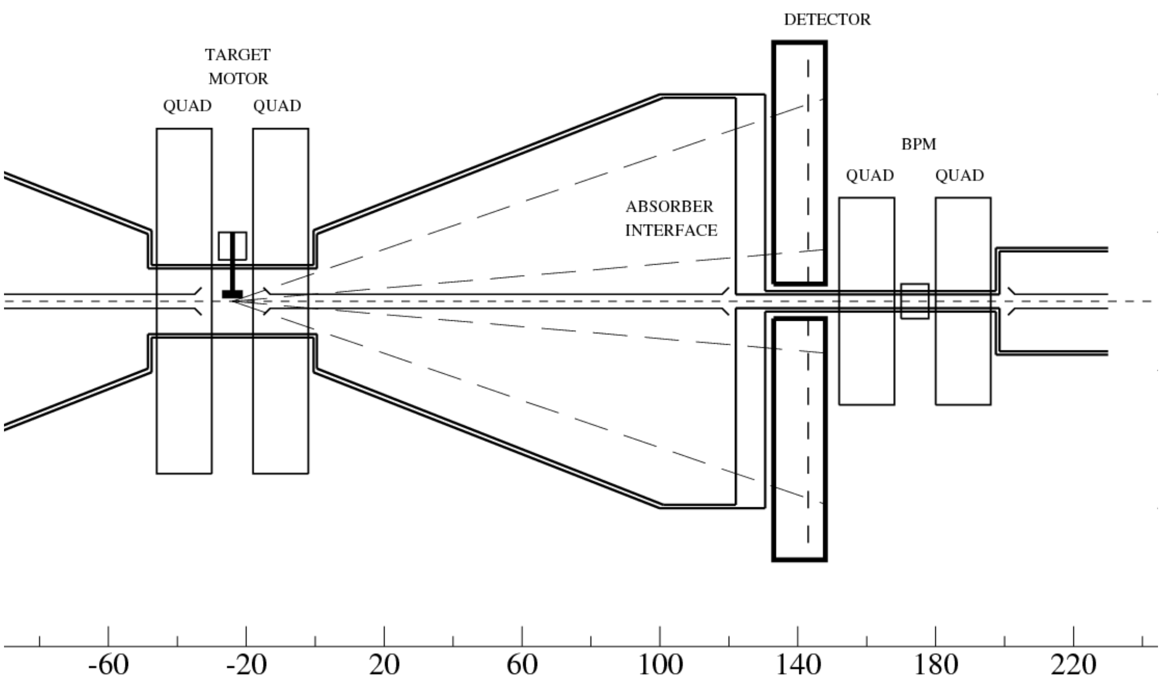
Fermi would need to get into polarized beams physics

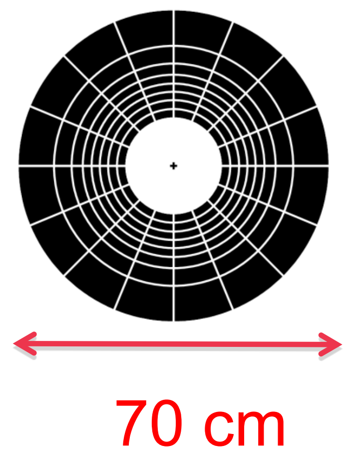
Proton EDM R&D cost: $2M

- BPM development & testing over two years: $0.6M
- E-field prototype development & testing: 1.8 years: $0.4M
- SCT tests at COSY, 2 years: $0.4M
- Polarimeter prototype, 2 years: $0.6M

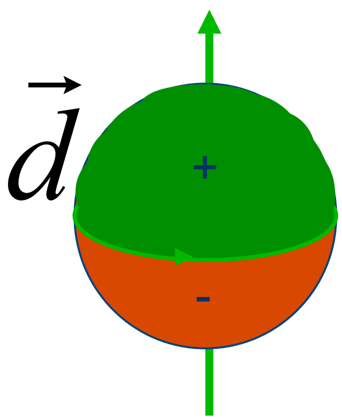
Polarimeter rates:

•Beam intensity with 2×10^{10} pol. protons/ $\sim10^{3}$s and a detection efficiency of 1% → 200KHz for ~3000cm^2 area, or ~100Hz/cm^2 on average but much higher at small radius. Design: ~1KHz/pad.





The Electric Dipole Moment precesses in an Electric field



The EDM vector *d* is along the particle spin direction

$$\boxed{\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}}$$

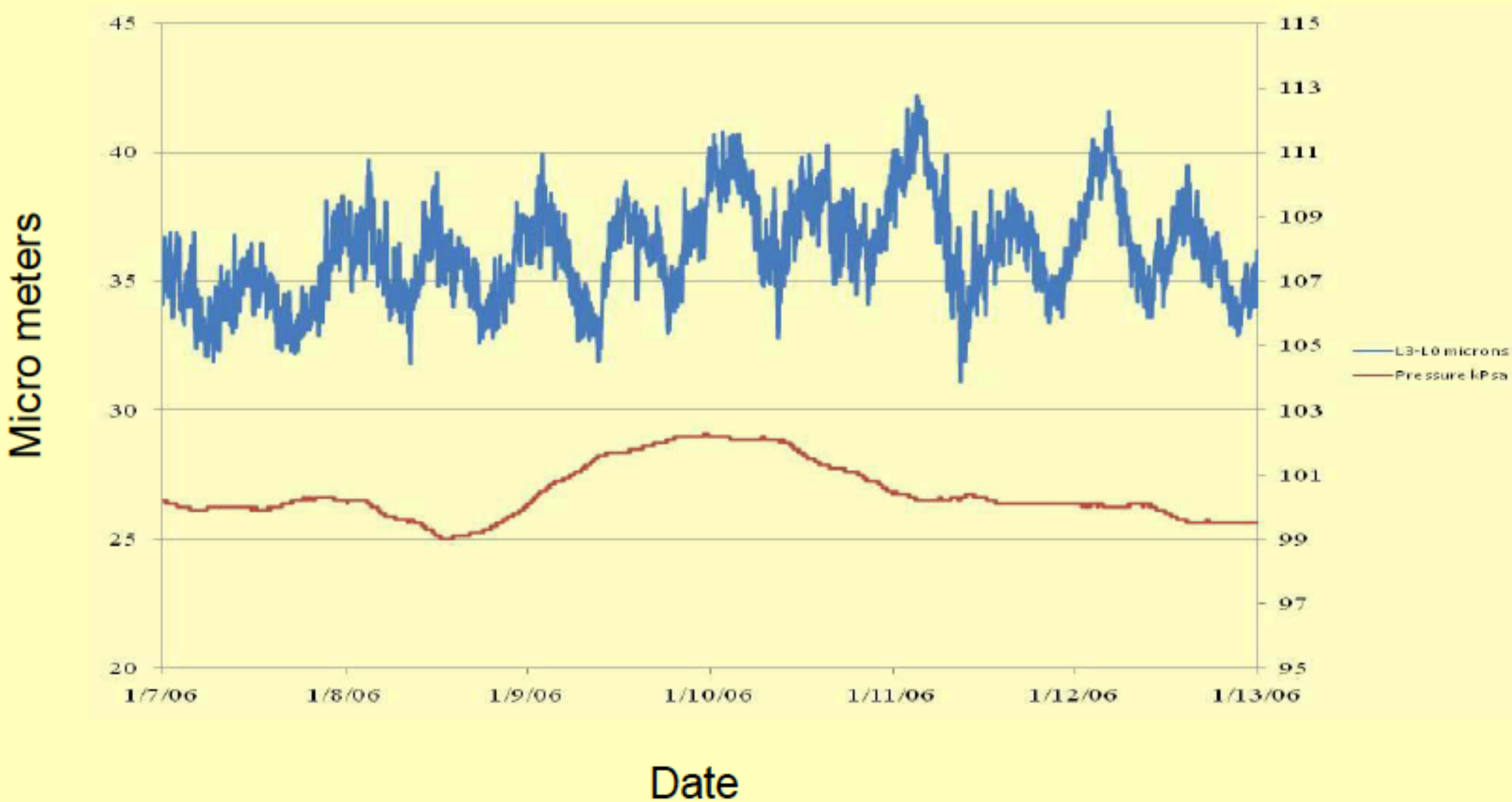
Parameters of current lattice

Table 2. The table of parameters for the proton EDM ring is shown here. The lattice has been estimated using the exact electric field and not an effective dipole magnetic field.

Parameter	**Value**	**Comment**
Proton Momentum	0.7007405 GeV/c	Kinetic energy: 232.8 MeV, $\beta = 0.59838$, $\gamma = 1.2481$
Ring bending radius	40 m	
Total length of straight sections	11.6 m	If more straight section length is needed the ring bending radius has to increase proportionally.
Radial E-field strength	10.5 MV/m	For plate separation of 3 cm the voltage on the plates is about ±160 KV.
Number of sections	16	The E-field plates within a section are ~16m long each. They can be segmented into 5 pieces, 3.14 m long each.
Radial E-field dependence at y=0	$R^{0.2}$	The E-field is slightly increased at larger radius.
Total length of orbit	263 m	
Horizontal tune	1.3	
Vertical tune	0.2-0.1	To be modulated by ~10% around 0.1
$\beta_{x,max}$	28 m	Horizontal aperture: 3 cm
$\beta_{y,max}$	240 m	Vertical aperture: 8 cm
Cyclotron frequency	0.6839 MHz	
$f_{rf} = 135 \times 0.6839$ MHz	90 MHz	Total RF voltage: 5 KV for synchrotron tune of 0.01
Slip factor	0.45	Sign is – (TBC)

MINOS Tidal Data

Difference in two sensors 90 meters apart



J T Volk Fermilab Dec 2008

Why COSY?

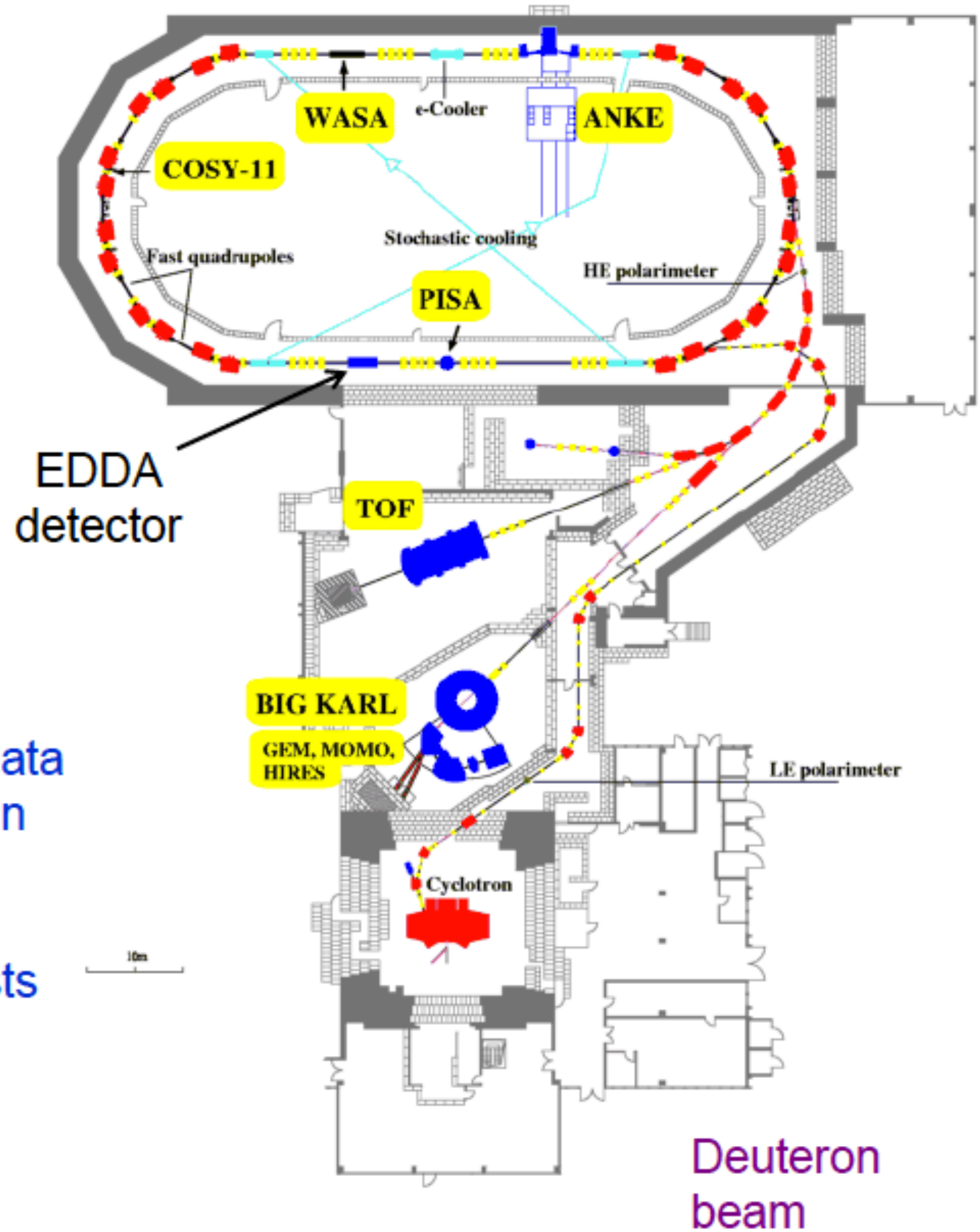
Scale like EDM ring
Polarized P/D beams
Electron cooling
Outside user program
Available equipment

History

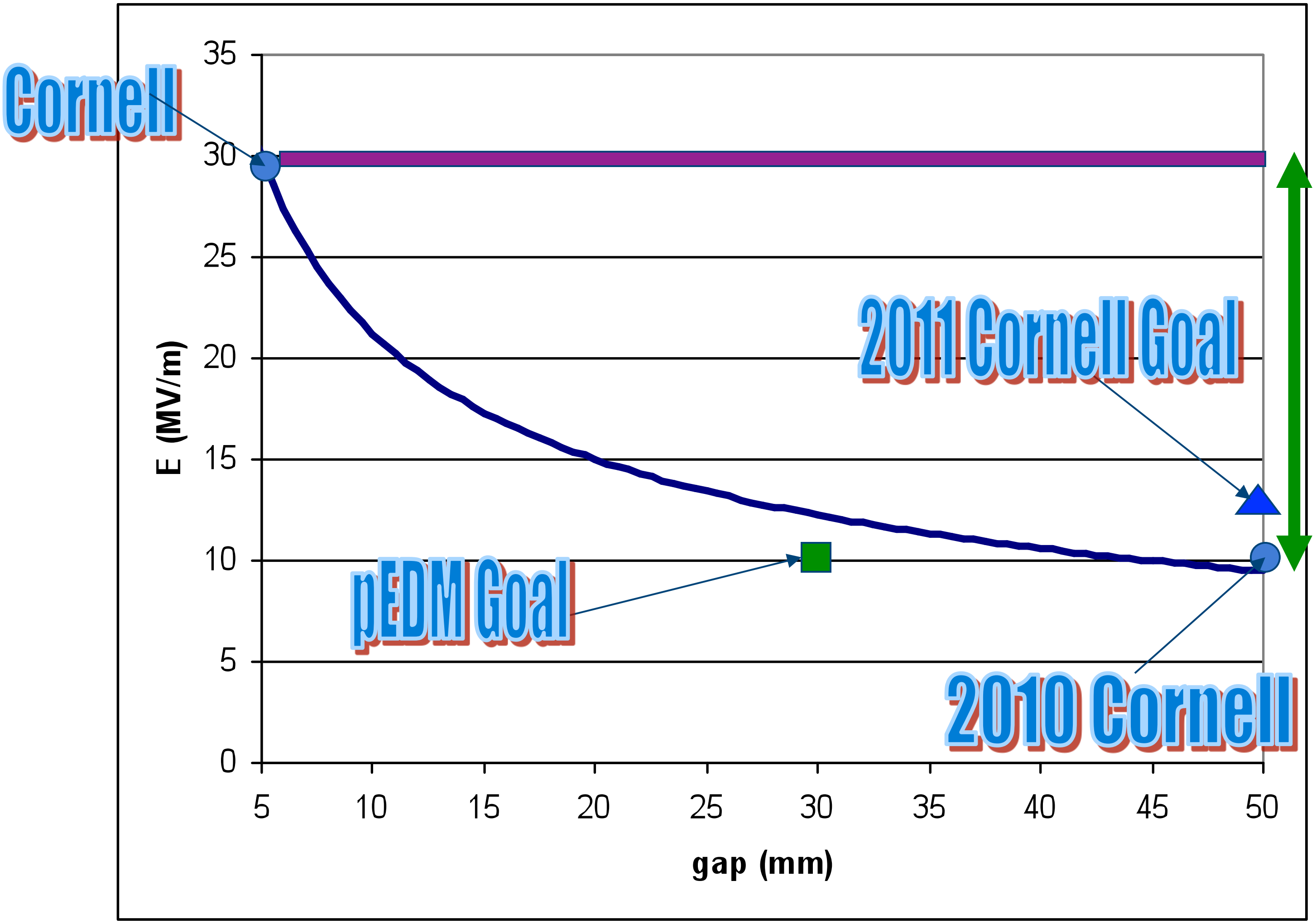
Proposal in 2007
Visit SPIN@COSY run
Three polarimeter runs:
- June 2008 – initial tests
- September 2008 – trial data
- June 2009 – final long run
  (paper in preparation)

Polarization lifetime runs:
- January 2011 – initial tests

Prior work at KVI, Groningen
- d=C data, 2004 + 2005
- Systematic errors, 2007

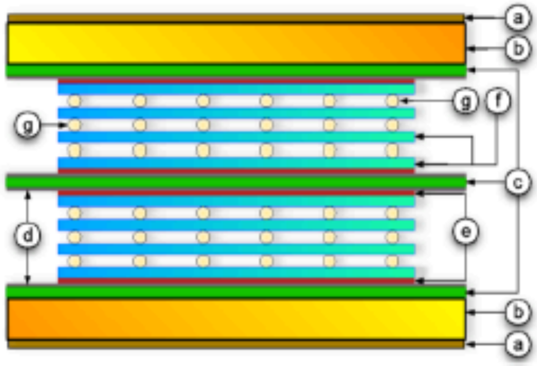


How to Scale HPWR to 3cm gap?



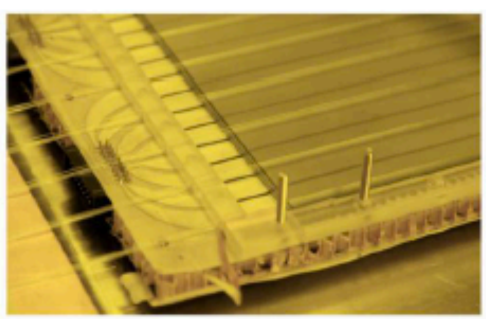
Detector systems: alternatives to scintillators

A Multi-resistive plate chambers(Italy)

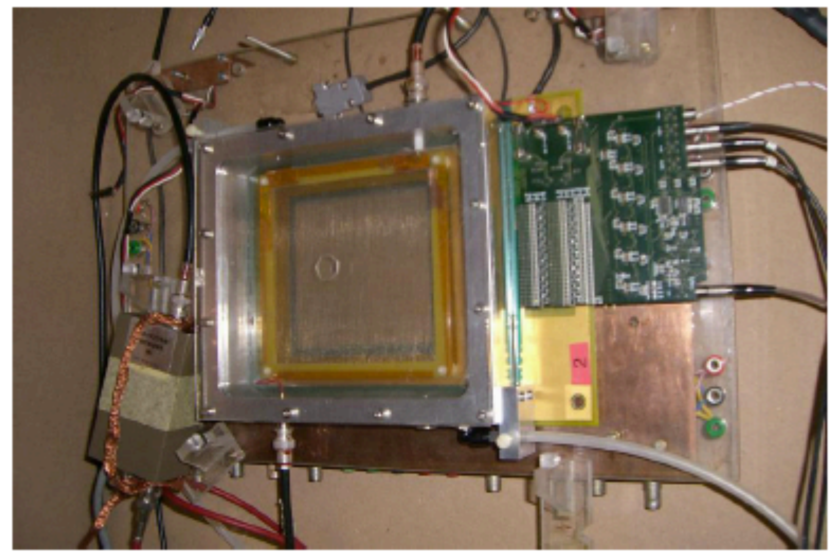


pickup electrodes (green)
also shown in photograph

The 20cm x 50cm prototype



B Micro-megas avalanche detection system Greece)



C Gas electron multiplier (GEM) system

In-beam tests are needed (COSY) to provide sample data sets.

Gas cluster ion beam surface treatment: getting rid of ~μm level asperities

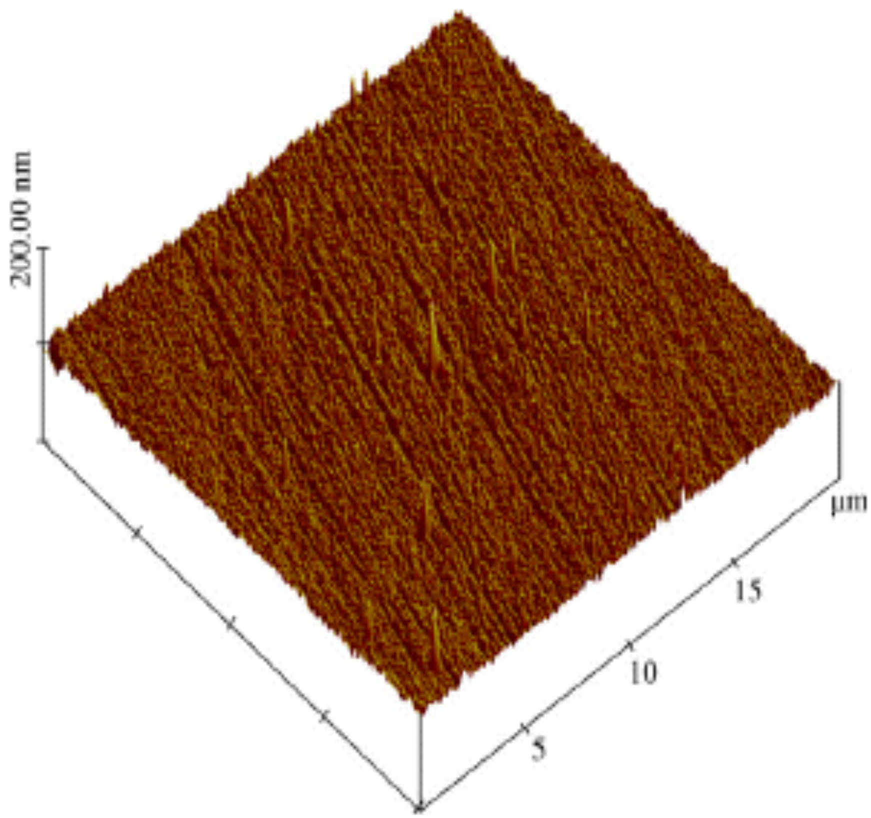


Fig. 1. AFM image (20×20 μm) of highly polished stainless steel electrode material before GCIB treatment showing asperities and scratch marks from polishing. The vertical scale is 120 nm/division.

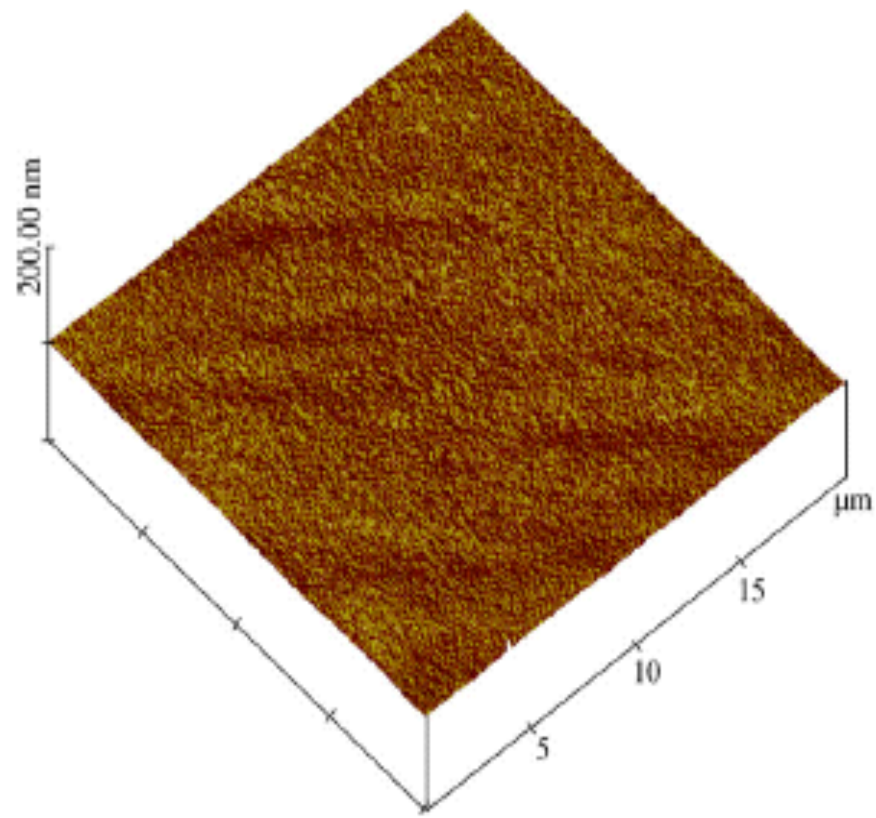
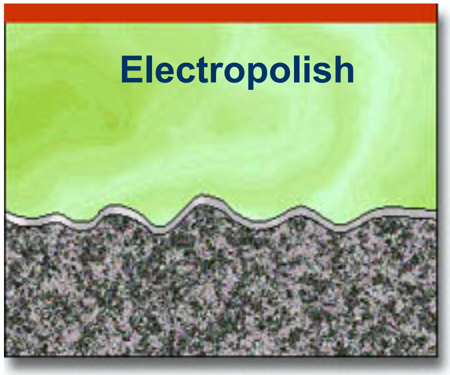


Fig. 2. AFM image (20×20 μm) of highly polished stainless steel electrode material after GCIB treatment. The vertical scale is 120 nm/division.

Electropolishing Process Verses Mechanical Polishing

Roughness: 4 - 40 microinches
(depends from abrasive grit number)

Mechanical polishing is an operation designed to prepare a metal surface for electropolishing or to satisfy non-critical surface roughness requirements. Mechanical polishing reduces all surface ridges, microprotrusions, pits and discrepancies to provide a homogeneous appearance and roughness.



Roughness: 2 - 5 microinches

Electropolishing (used since early 1950's) is the electrochemical removal of microscopic irregularities or diminution scratches, burns and unwanted harp edges from metal surfaces. Typical material removal is .0001"- .0004"
per surface.

Smoothness of the metal surface is one of the primary and most advantageous effects of electropolishing.

<u>Electropolishing should improve separator performance.</u>

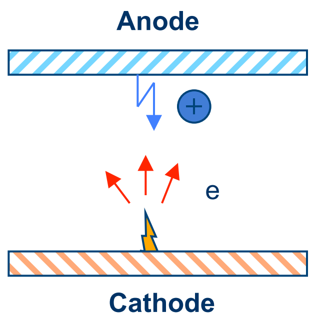
High Voltage Electrical Breakdown in Vacuum

It is generally agreed that a vacuum breakdown is a vapor arc, taking place in material evaporated from the electrodes. Evidence is the observation of localized light during breakdown and electrode material transferred across the gap.

- **Electron field emission mechanism for initiating the breakdown**

  According with this model, electrons are assumed to be field emitted from the tip of microprotrusion at an isolated site on the surface of broad-area cathode. Question: where is the metal vapor produced at the anode or cathode?

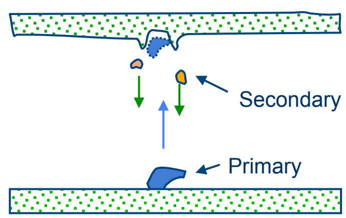
  Is it enough power to vaporize anode material by field emitted electrons bombarded anode or positive ions produced at the anode lead to rupture of the cathode or that resistive heating on the cathode causes them to melt and ultimately to vaporize. <u>This mechanism dominates at gaps less than 2 mm.</u>



- **Microparticle or "clump" model**

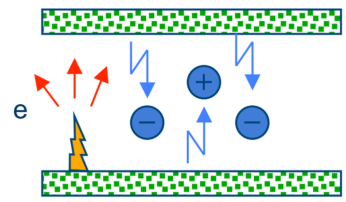
  Clump of loosely adhesive material is drawn across the gap by the electric field so as to strike the opposite electrode with enough energy to produce high local temperature in the electrode or clump material with melting and vaporizing.

  <u>Pre-operational electrode surface will be characterized by having a finite number of microscopic particles.</u> These will originate from various stages of mechanical polishing, and may be in the form of either impurity particle of polishing material or dust particles. Another source of microparticles are those originated from thermal instabilities at either the cathode or anode "hot" spot. For uniform gaps the breakdown voltage should vary as the square root of the gap spacing. The model is dominating at large gaps.



- **Ion exchange mechanism**

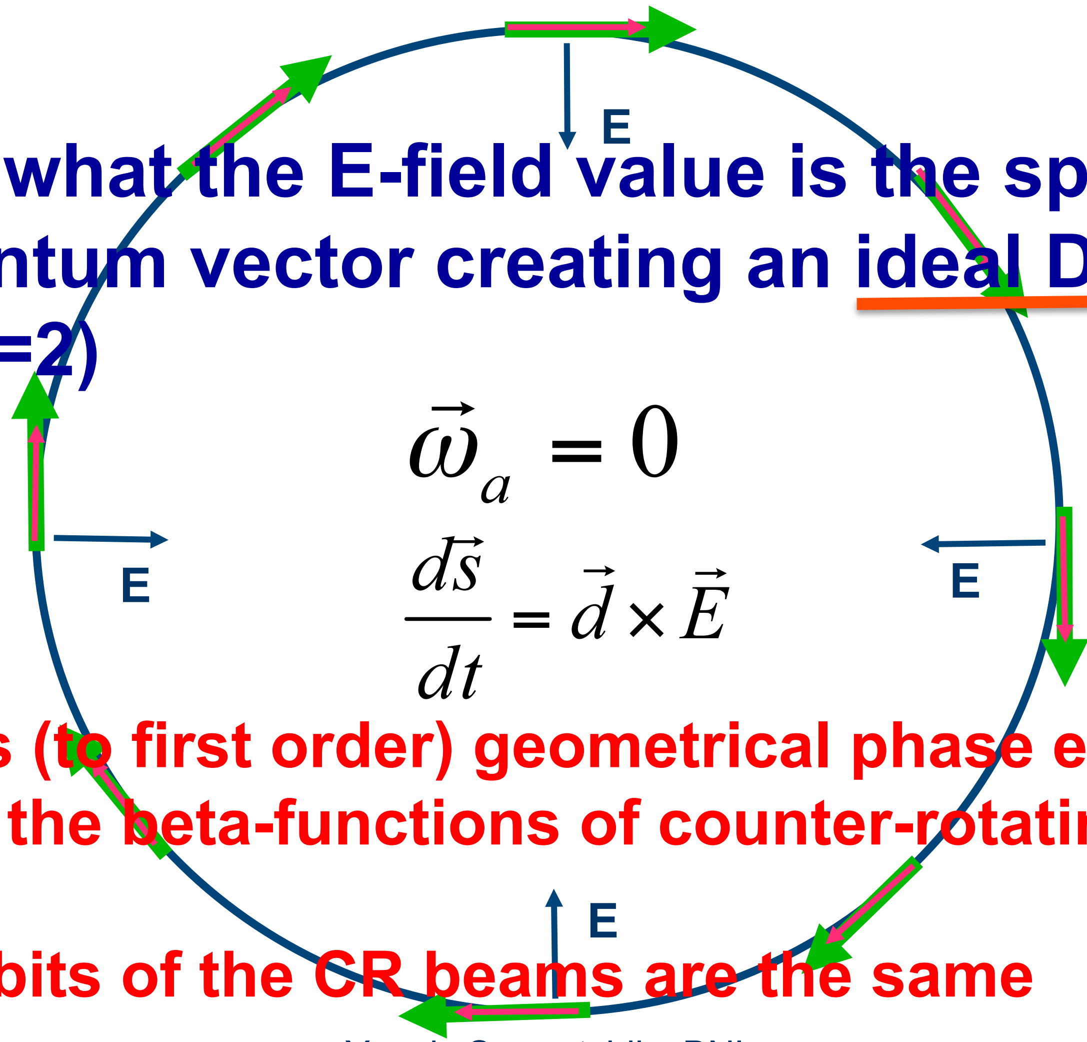
  This mechanism is assumed to be initiated by say random positive ion created in the gap that is then accelerated by the field to generate further negative ions on impact with cathode, which subsequently generate more positive ions on impact with the anode etc. Thus, if the ion multiplication factor > 1, the process will develop in the breakdown mode. It is very sensitive to chemicals contaminations.



The breakdown consists of many complicated and complex phenomena with no single process involved.

When $P=P_{magic}$ the spin follows the momentum

No matter what the E-field value is the spin follows the momentum vector creating an ideal Dirac-like particle (g=2)



$$\vec{\omega}_a = 0$$

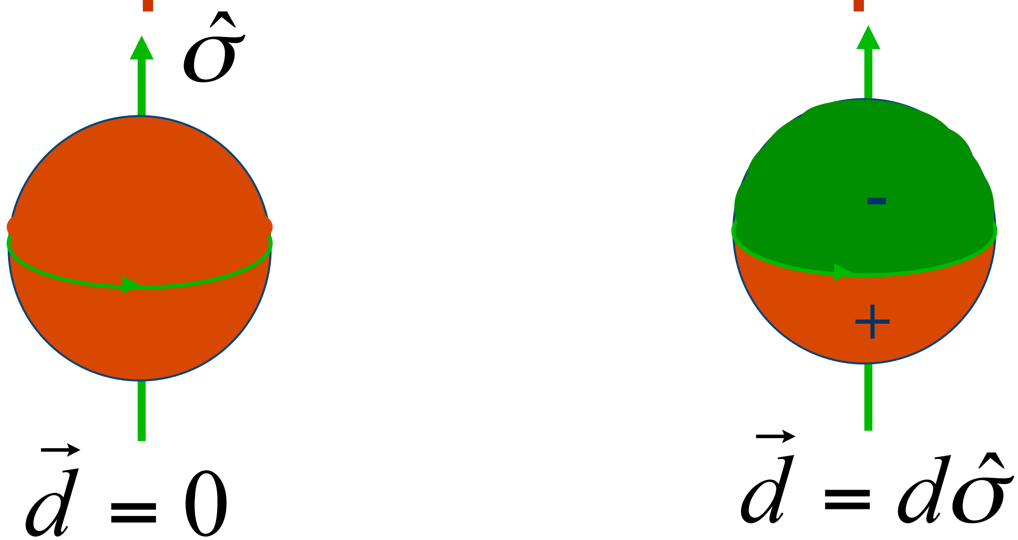
$$\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}$$

1. **Eliminates (to first order) geometrical phase effect**
2. **Equalizes the beta-functions of counter-rotating (CR) beams**
3. **Closed orbits of the CR beams are the same**

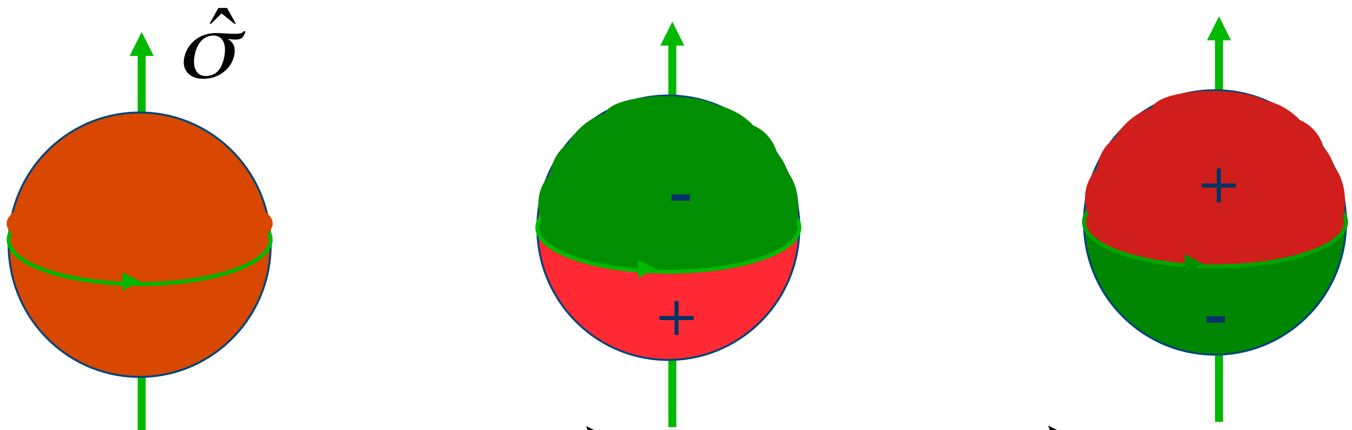
Physics/effort comparison

- Physics reach ~10^3 TeV, similar to mu2e (MECO) experiment at FNAL; moreover, it can explain BAU (EW-Baryogenesis)
- SUSY-like new physics at LHC scale, it probes CP-violating phases to sub micro-radian level, complementary to LHC (plus fine-tuned SUSY)
- At 10^{-29}e·cm it's > an order of magnitude better than the best neutron EDM plans anywhere. Statistically superior to neutron EDM exps.
- Method can be applied to proton, deuteron, and ^{3}He to unravel the underlying physics. More than other methods can do.

Spin is the only vector defining a direction of a “fundamental” particle with spin



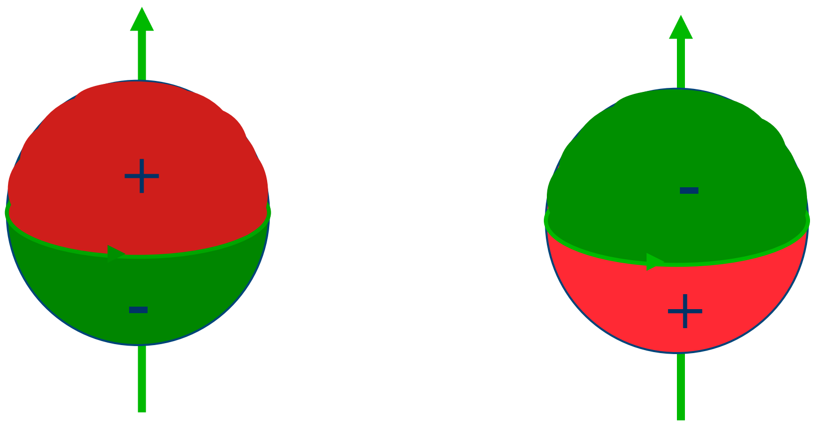
Electric Dipole Moment: two possibilities



$\vec{d} = 0$ $\vec{d} = d\hat{\sigma}$ $\vec{d} = -d\hat{\sigma}$

If we discover that the proton

- Has a non-zero EDM value, i.e. prefers only one of the two possible states:



- Then P and T symmetries are violated and through CPT, CP-symmetry is also violated.
- CP-violation is one of three necessary conditions to obtain a matter dominated universe starting from a symmetric one…

Purcell and Ramsey:

"The question of the possible existence of an electric dipole moment of a nucleus or of an elementary particle…becomes a purely <u>experimental</u> matter"

Phys. Rev. 78 (1950)

2. Polarimeter Development

- ✓ Polarimeter tests with runs at COSY (Germany) demonstrated < 1ppm level systematic errors: N. Brantjes et al., NIM A **664**, 49, (2012)

- Technologies under investigation:

1. Micro-Megas/Greece: high rate, pointing capabilities, part of R&D for ATLAS upgrade
2. MRPC/Italy: high energy resolution, high rate capability, part of ALICE development

3. Spin Coherence Time: need >10^2 s

- Not all particles have same deviation from magic momentum, or same horizontal and vertical divergence (all second order effects)

- They cause a spread in the g-2 frequencies:

$$d\omega_a = a\vartheta_x^2 + b\vartheta_y^2 + c\left(\frac{dP}{P}\right)^2$$

- Present design parameters allow for 10^3 s. Cooling/mixing during storage could prolong SCT (upgrade option?).

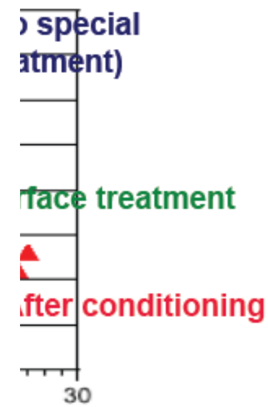
SCT Development

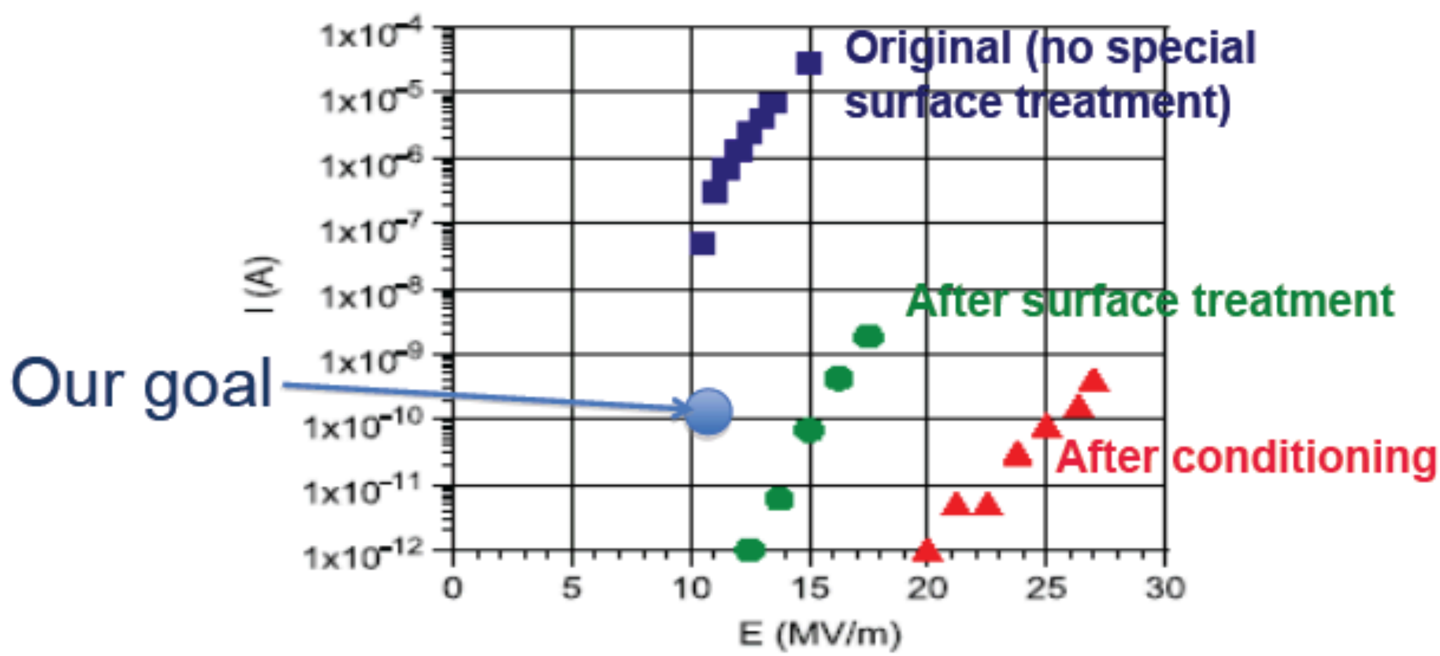
- We have a SCT working solution (precision tracking and analytically-work in progress).
- Tests with polarized deuterons and protons at COSY to benchmark software (underway)
- Test runs at COSY are very encouraging.
- Bonus: Electric ring with weak vertical focusing →SCT is long enough for 10^3s storage

4. Electric Field Development

- ✓ Reproduce Cornell/JLAB results of stainless steel plates treated with high pressure water rinsing (part of ILC/ERL development work)

Recent Progress from ILC/ERL R&D (~5mm gap tests) Cornell/JLab





Large Scale Electrodes, New: pEDM electrodes with HPWR

Parameter	Tevatron pbar-p Separators	BNL K-pi Separators	pEDM
Length	2.6m	4.5m	3m
Gap	5cm	10cm	3cm
Height	0.2m	0.4m	0.2m
Number	24	2	10^2
Max. HV	±180KV	±200KV	±150KV

Important Stages in an EDM Experiment

1. Polarize: state preparation, intensity of beams
2. Interact with an E-field: the higher the better
3. Analyze: high efficiency analyzer
4. Scientific Interpretation of Result! Easier for the simpler systems (theory; lattice?)

The grand issues in the proton EDM experiment

1. BPM magnetometers (need to demonstrate in a storage ring environment)
2. Polarimeter development: high efficiency, small systematic errors
3. Spin Coherence Time (SCT): study at COSY/ simulations; Simulations for an all-electric ring: SCT and systematic error studies
4. Electric field development for large surface area plates

A proposed proton EDM ring location at BNL. It would be the largest diameter all-electric ring in the world.

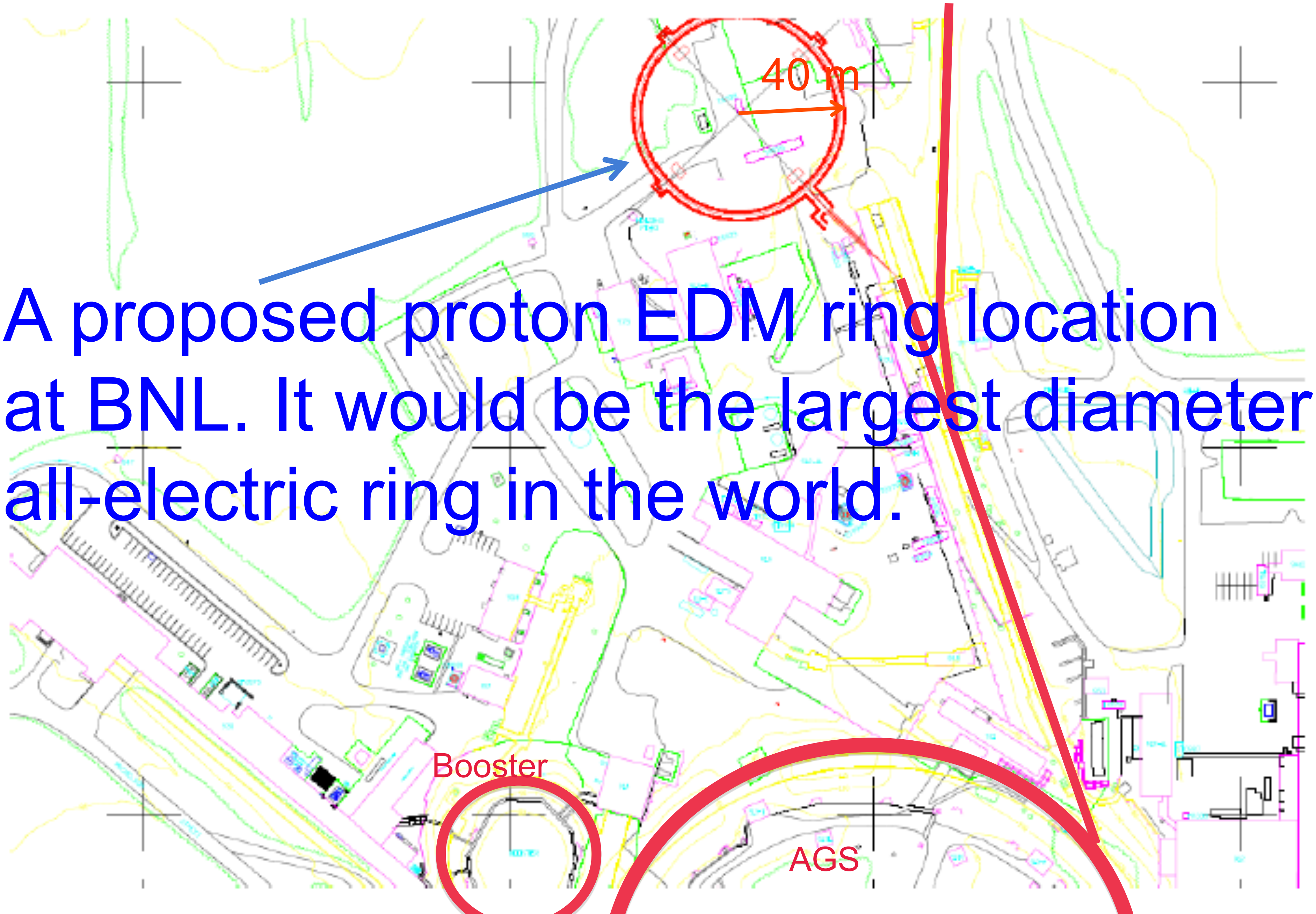


Figure 6 Storage Ring location in the North Area

Total cost: exp + ring + beamline for two different ring locations @ BNL

System	Experiment w/ indirects	Conventional plus beamline w/ indirects	Total
pEDM at ATR	$25.6M	$20M	$45.6M
pEDM at SEB	$25.6M	$14M	$39.6M

System	Experiment w/ 55% contingency	Conv. & Beamline w/ contingency	Total
pEDM at ATR	$39.5M	$29.2M	**$68.7M**
pEDM at SEB	$39.5M	$22.6M	**$62.1M**

EDM ring

EDM ring+tunnel and beam line

Storage Ring EDM Collaboration

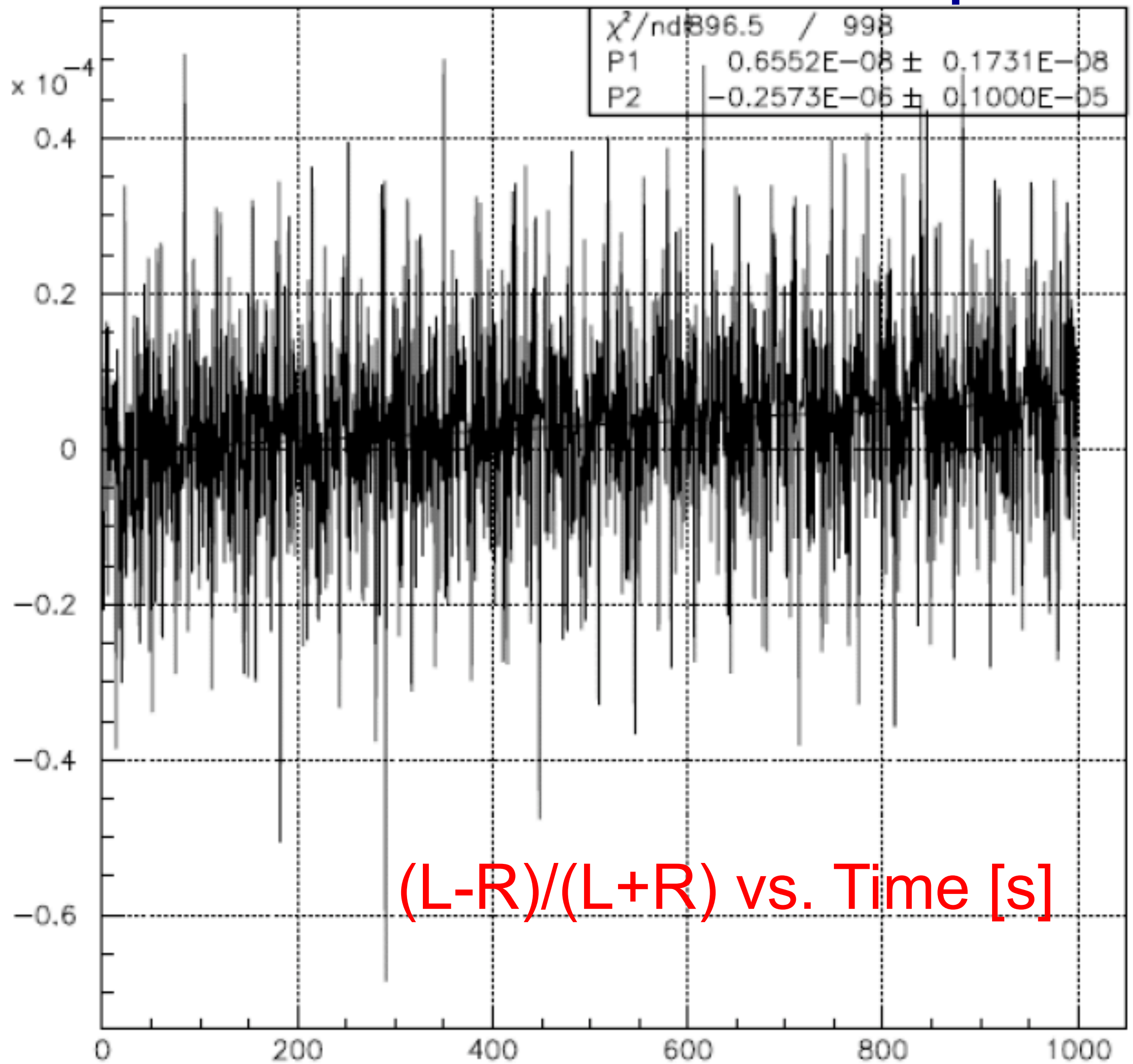
>20 Institutions
>80 Collaborators

- Aristotle University of Thessaloniki, Thessaloniki/Greece
- Research Inst. for Nuclear Problems, Belarusian State University, Minsk/Belarus
- Brookhaven National Laboratory, Upton, NY/USA
- Budker Institute for Nuclear Physics, Novosibirsk/Russia
- Royal Holloway, University of London, Egham, Surrey, UK
- Cornell University, Ithaca, NY/USA
- Institut für Kernphysik and Jülich Centre for Hadron Physics Forschungszentrum Jülich, Jülich/Germany
- Institute of Nuclear Physics Demokritos, Athens/Greece
- University and INFN Ferrara, Ferrara/Italy
- Laboratori Nazionali di Frascati dell'INFN, Frascati/Italy
- Joint Institute for Nuclear Research, Dubna/Russia
- Indiana University, Indiana/USA
- Istanbul Technical University, Istanbul/Turkey
- University of Massachusetts, Amherst, Massachusetts/USA
- Michigan State University, East Lansing, Minnesota/USA
- Dipartimento do Fisica, Universita' "Tor Vergata" and Sezione INFN, Rome/Italy
- University of Patras, Patras/Greece
- CEA, Saclay, Paris/France
- KEK, High Energy Accel. Res. Organization, Tsukuba, Ibaraki 305-0801, Japan
- University of Virginia, Virginia/USA

http://www.bnl.gov/edm

The EDM signal: early to late change

- Comparing the (left-right)/(left+right) counts vs. time we monitor the vertical component of spin



M.C. data

Figure 2. (L-R)/(L+R) vs. time [s] is shown here as well as the fit results to two parameters (slope and dc offset). More details on the parameters used are given in table 1